The cuprate phase diagram: insights from neutron scattering and electrical transport

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Acknowledgements

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CRYSTAL GROWTH

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ELECTRICAL TRANSPORT

N. Barišić (CEA-Saclay, France, Vienna University of Technology, Austria)

W. Tabis, M. Veit ,Y. Li (UMN)

C. Proust (Toulouse, France)

NEUTRON SCATTERING

Y. Tang, C. Dorow, M. Veit (UMN)

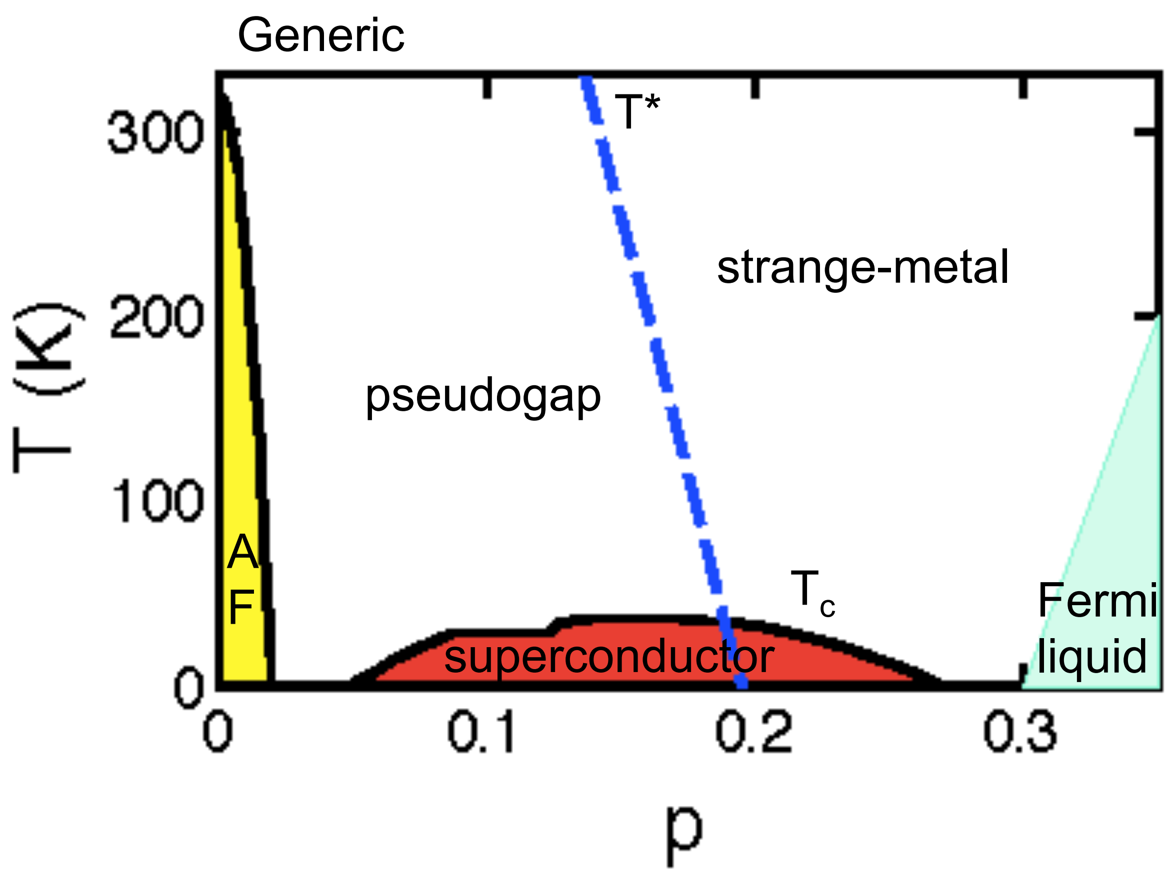
L. Mangin-Thro, Y. Sidis, P. Bourges (LLB, CEA-Saclay, France)

D. L. Abernathy, A. D. Christianson (ORNL, USA)

P. Steffens (ILL, Grenoble, France)

J.T. Park (FRM-II, Garching, Germany)

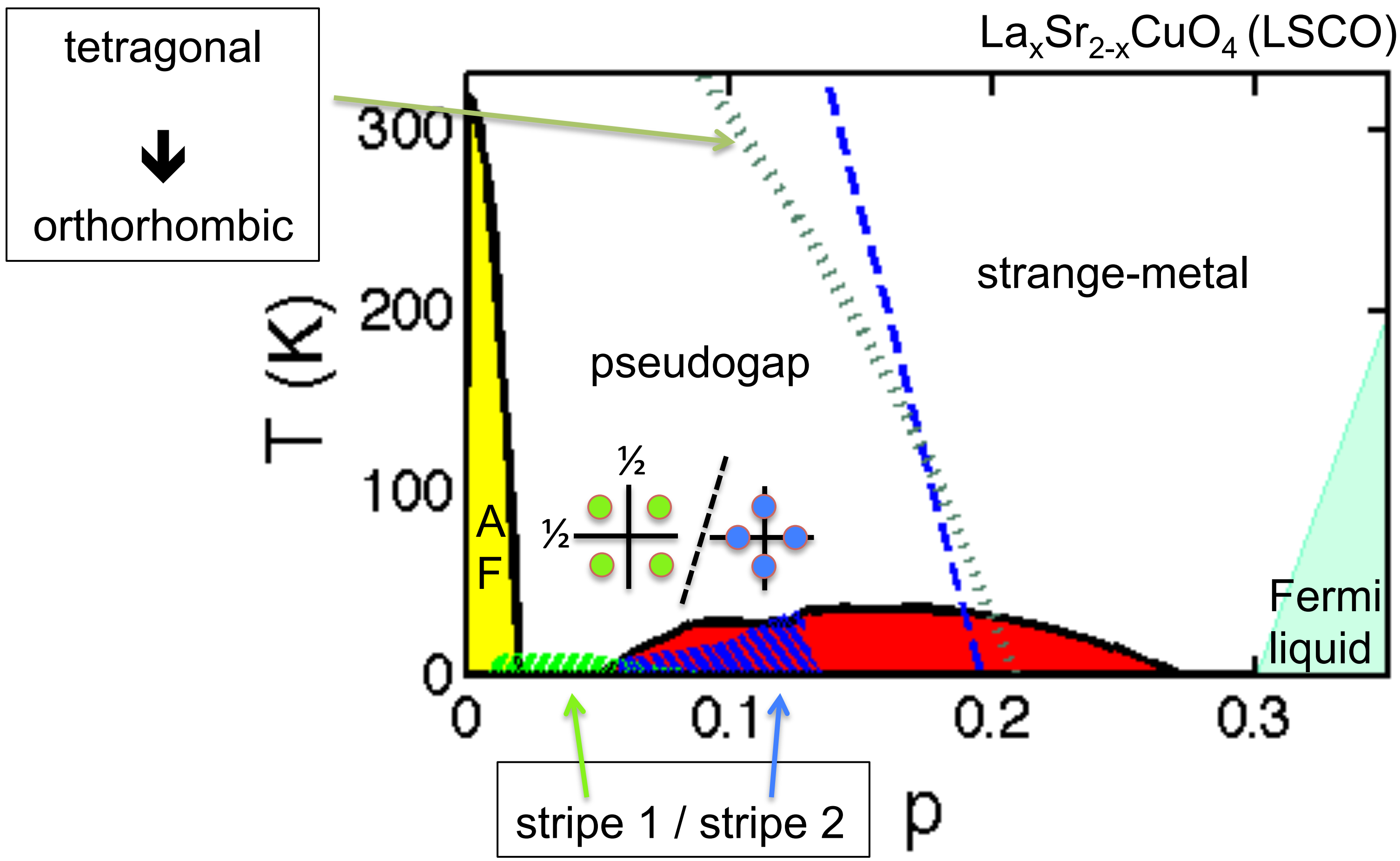
Cuprate phase diagram



- Insulating parent compound: localized spins with antiferromagnetic order
- Fermi-liquid at very high doping

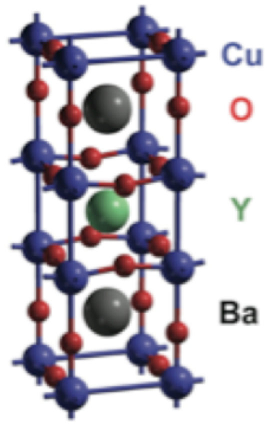
Structural transitions and competing phases

- Why is high-T_c a hard problem (experimentally)?
  - Disorder (e.g. Sr substitution) and structural transitions
  - Other ordering tendencies: Universal? Integral?



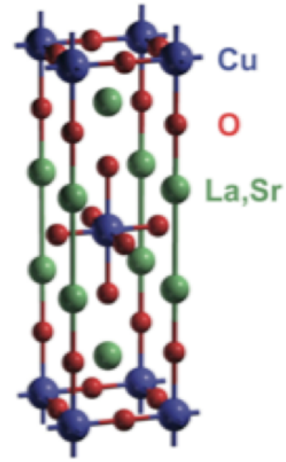
The most studied cuprates

$YBa_2Cu_3O_{7-\delta}$
(YBCO)

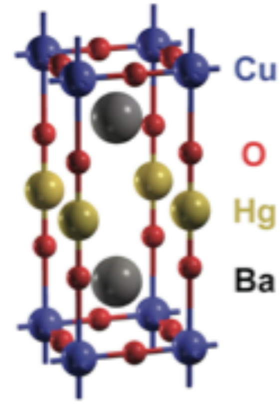


courtesy Guichuan Yu

$La_{2-x}Sr_xCuO_4$
(LSCO)



$HgBa_2CuO_{4+\delta}$
(Hg1201)

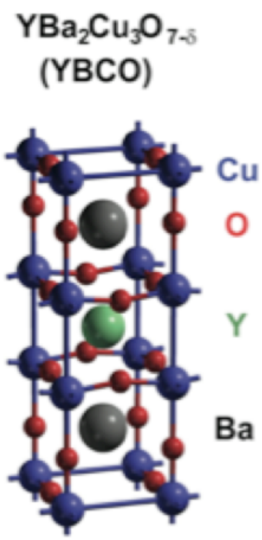


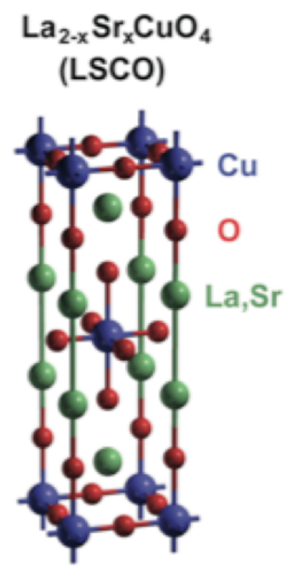
- CuO chains
- 2 x CuO_2 planes
- orthorhombic
- T_c^{max} = 93 K

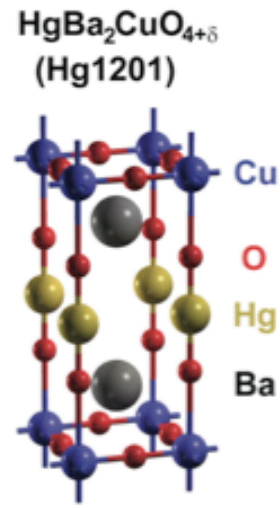
- No chains
- 1 x CuO_2 plane
- orthorhombic
- T_c^{max} = 40 K

- No CuO_2 chains
- 1 x CuO layer
- tetragonal
- T_c^{max} = 98 K (the highest of the single-layered cuprates)

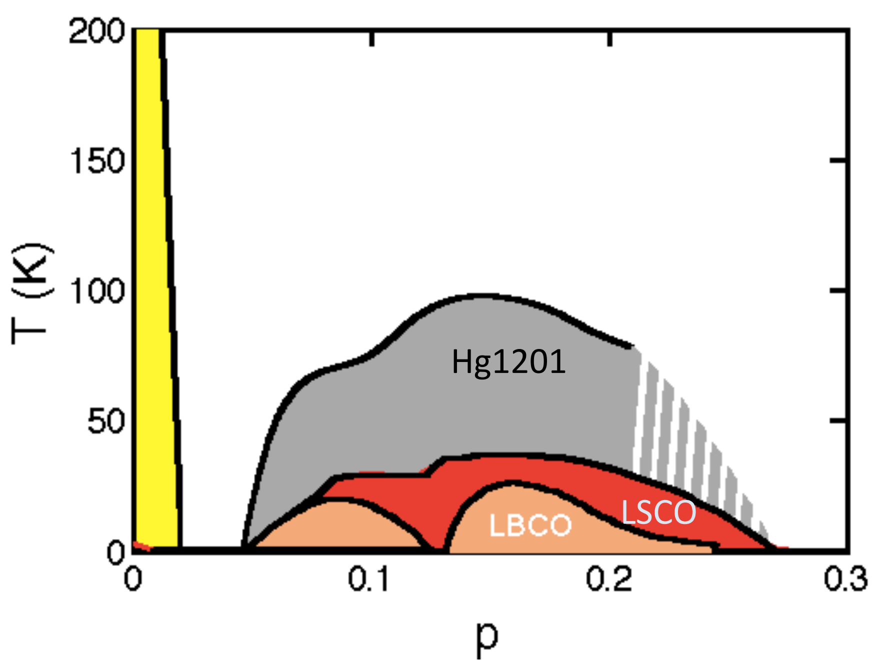
The most studied cuprates







courtesy Guichuan Yu

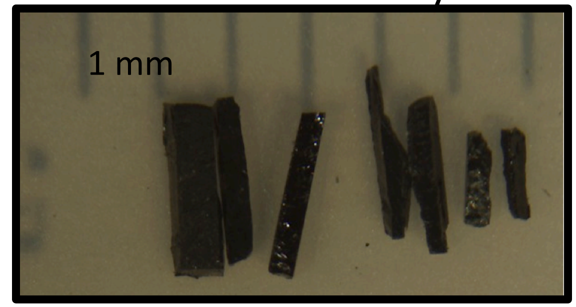


LBCO : $La_{2-x}Ba_xCuO_4$

Part 1: electrical transport

Mike Veit (senior, UMN)

cleaved crystals

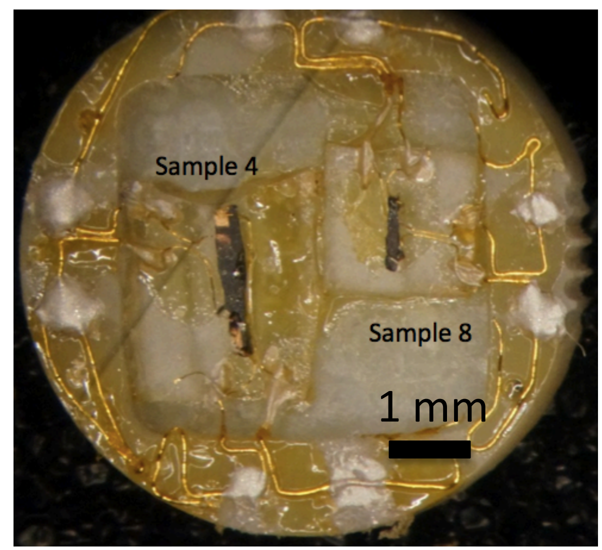


LNCMI-Toulouse, France
Baptiste Vignolle, Cyril Proust

Au pads+Ag paste

Vienna University of Technology, Austria
N. Barišić

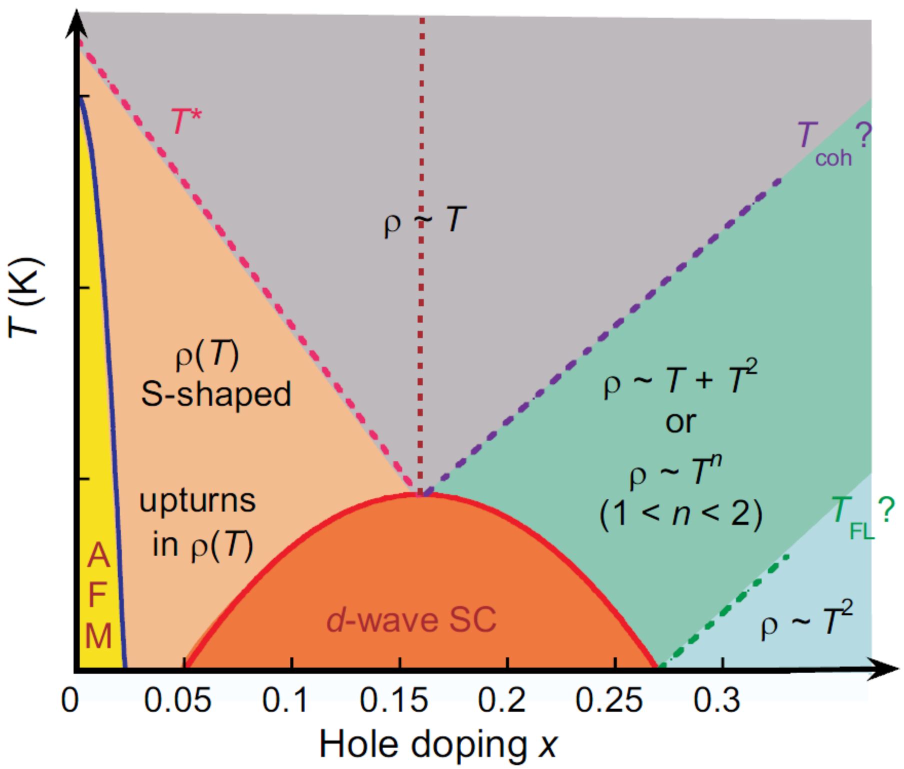
contacted and ready for pulse field

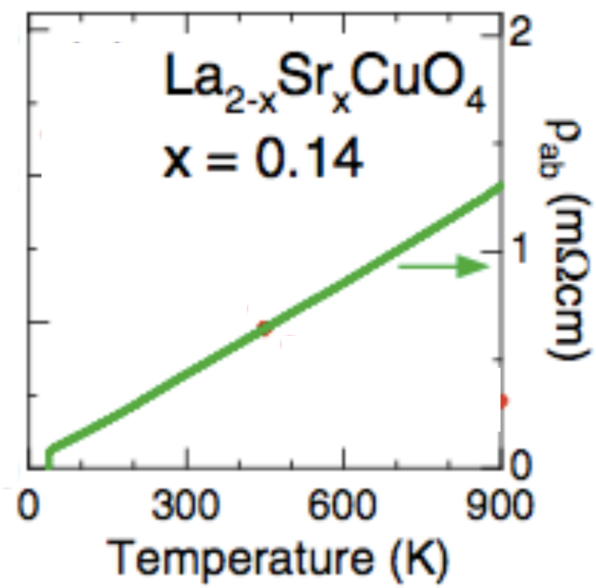


National High Magnetic Field Lab
Tallahassee and Los Alamos
A. Sheckter
R. McDonald

Resistivity (strange-metal)

- T- linear resistivity to very high temperatures





N. J. Hussey Phys.: Condens. Matter. (2008)

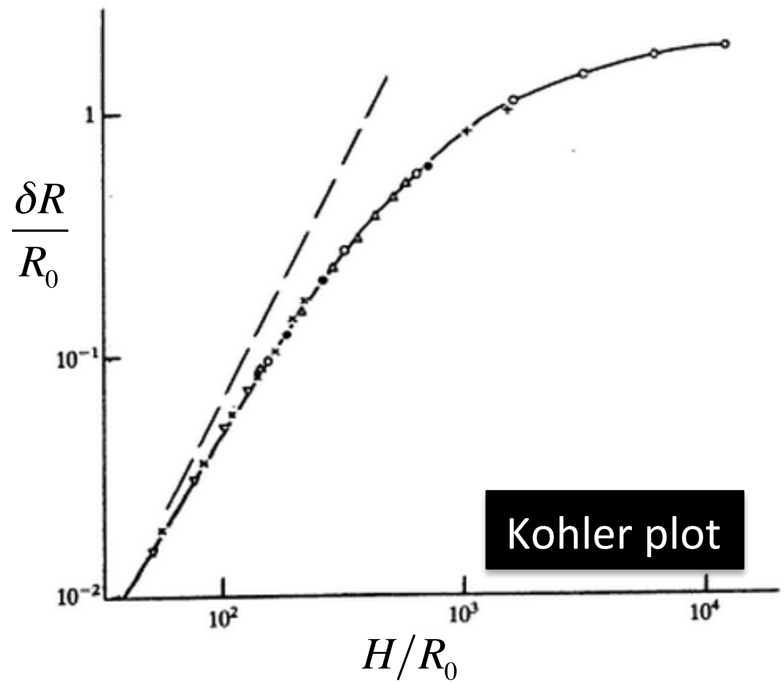
Y. Ando *et al.*, PRL (2004)

Magnetoresistance and Kohler's rule

Magnetic field	$H \to cH$
Scattering rate	$\frac{1}{\tau} \to c\frac{1}{\tau}$
Resistivity	$\rho \to c\rho$

$$\boxed{\frac{\rho(H)-\rho_0}{\rho_0} = \frac{\delta\rho}{\rho_0} = F\left(\frac{H}{\rho_0}\right)}$$

Indium with different impurity levels at the same temperature

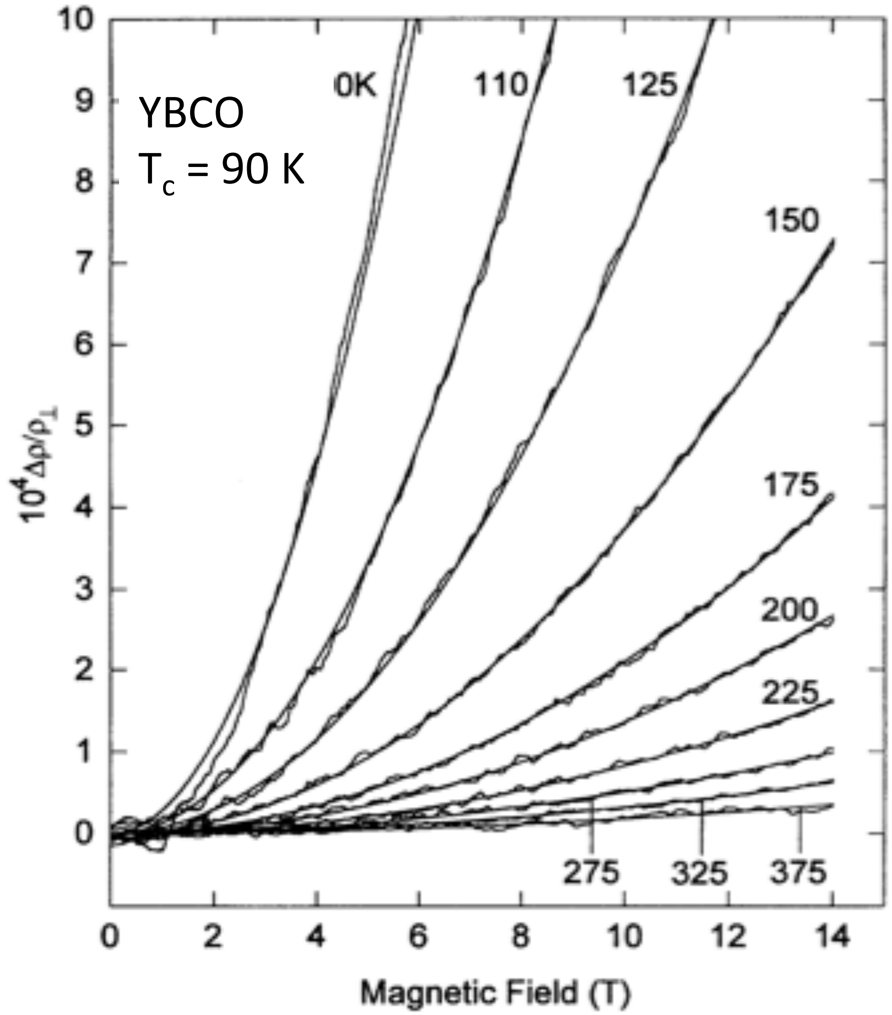


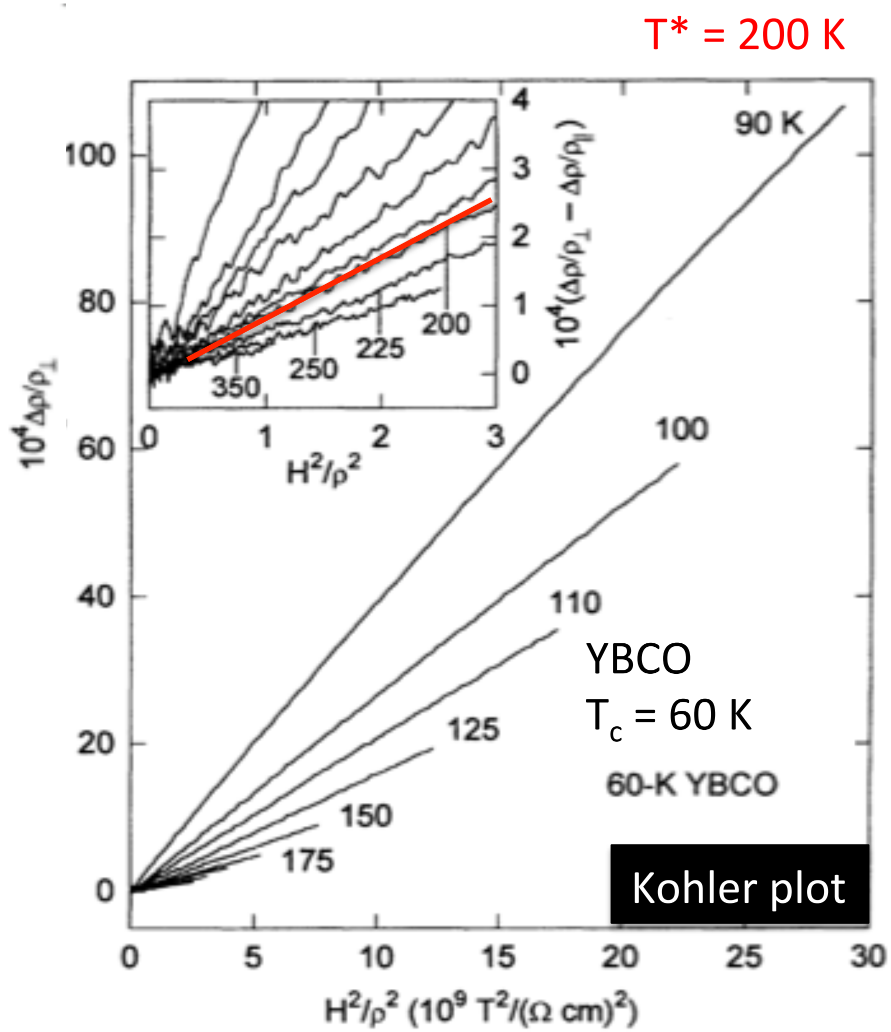
J. L. Olsen *Electron transport in metals* (1962)

- Contingent on:
  - Only the amount of scattering changes
  - Single scattering mechanism
  - Constant number of carriers

Violation of Kohler's rule

- Violation of Boltzmann kinetics





M. Harris *et al.* PRL (1995)

Explanations for unconventional transport

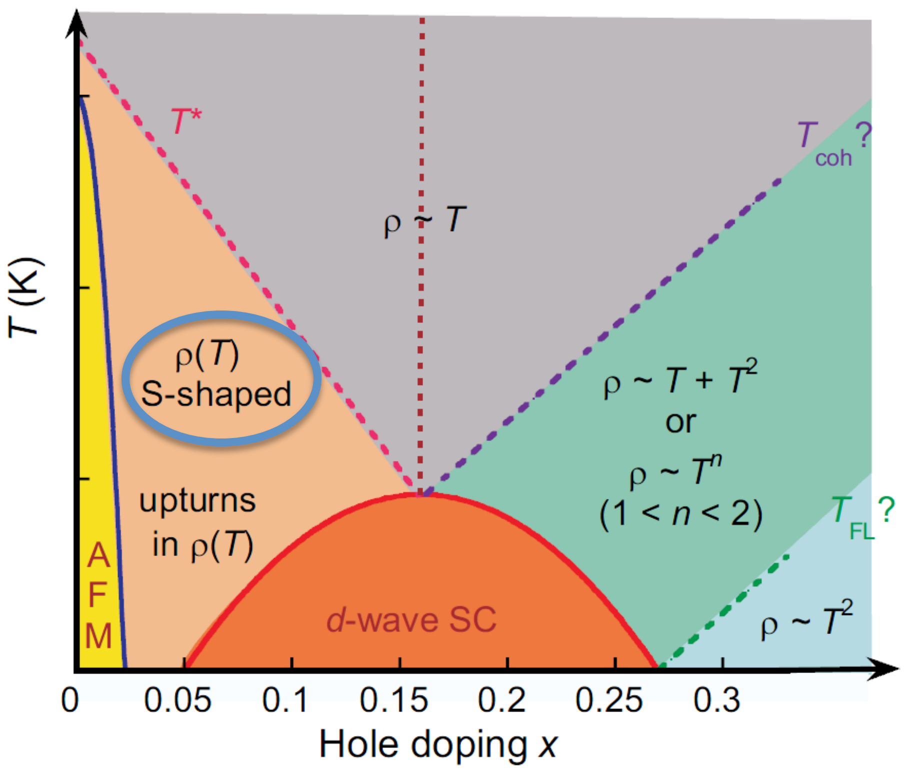
- Charge-spin separation (P. W. Anderson, Phys. Rev. Lett. **67**, 2092 (1991))

- Anisotropic Umklapp scattering (N. E. Hussey *et al.* PRL (1996))

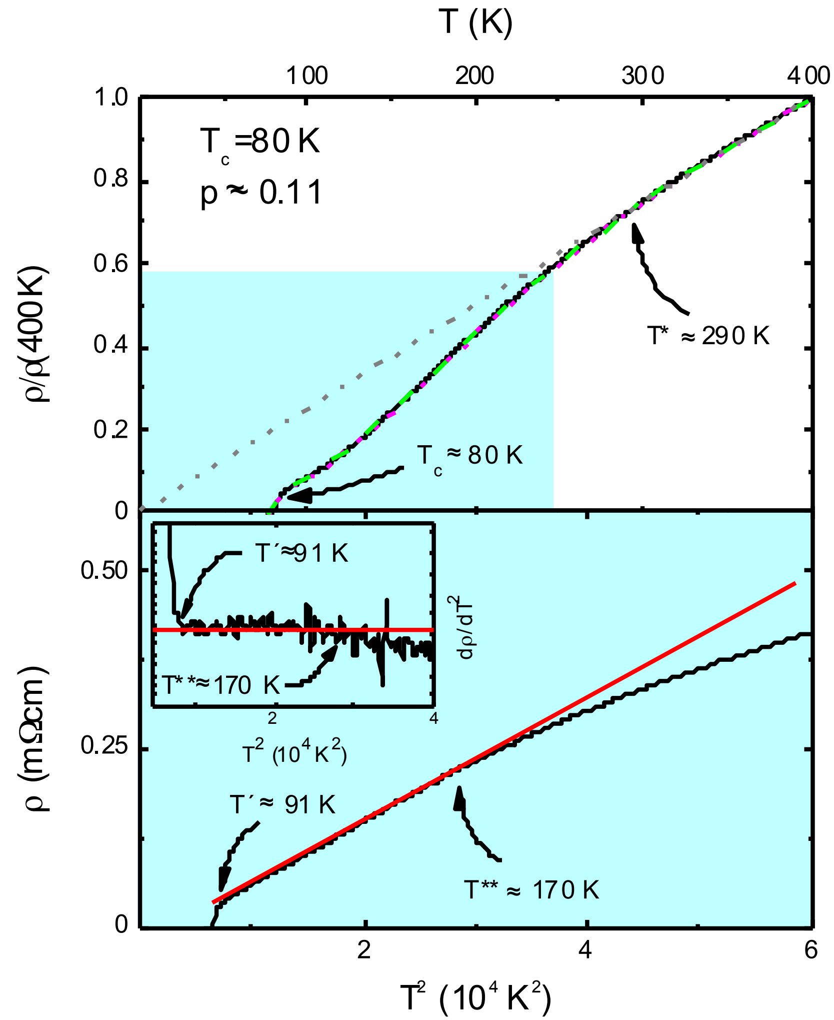
- Coupling to a bosonic mode
  - Spin fluctuations (P. Monthoux and D. Pines, PRB (1994))
  - Charge fluctuations (C. Castellani *et al.* PRL (1995))

Electrical transport in the pseudogap

- Electrical transport is ill-defined in the pseudogap phase
- Fluctuations of superconductivity or nearby ordered states



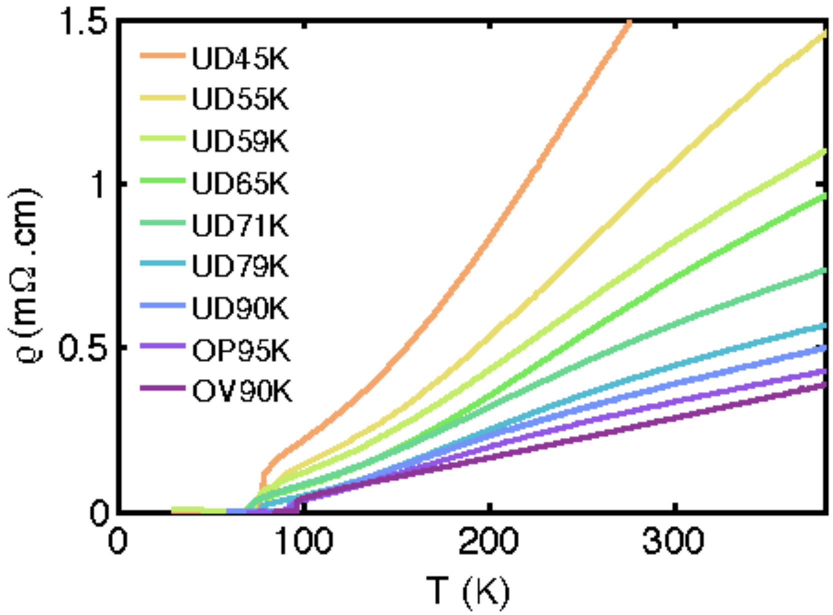
N. J. Hussey Phys.: Condens. Matter. (2008)



N. Barišić, MKC *et al*. PNAS (2013)

Electrical transport in the pseudogap

- Clear separation of a linear and quadratic regimes

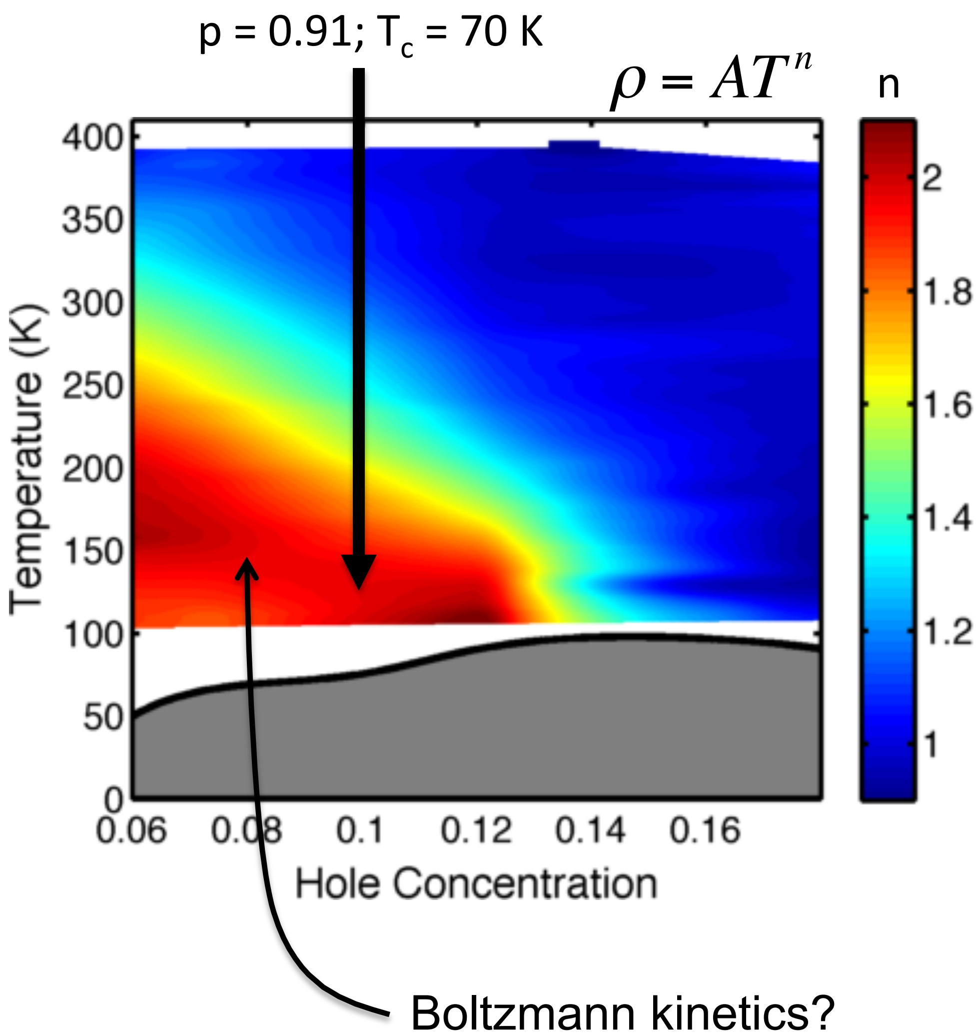


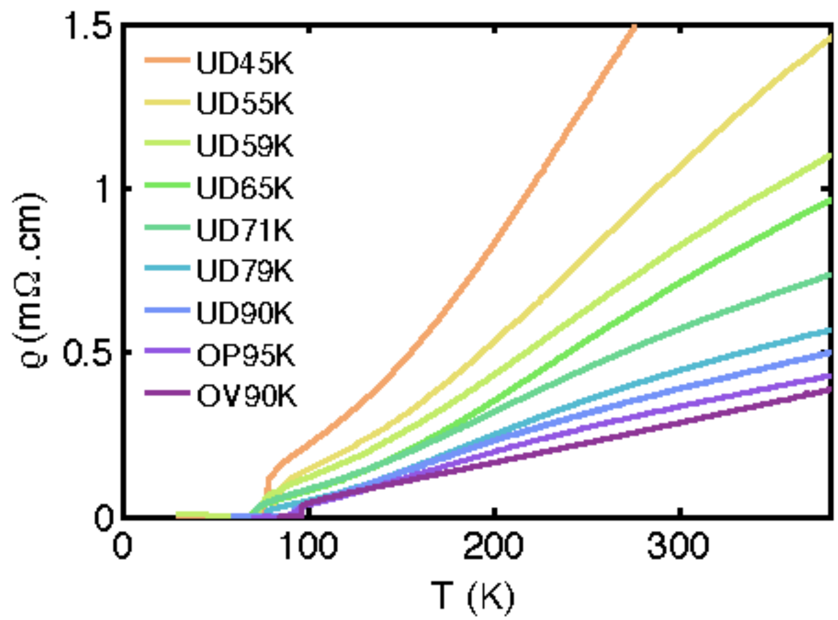
Boltzmann kinetics?

M .K. Chan *et al.* unpublished

Magnetoresistance

- Clear separation of a linear and quadratic regimes

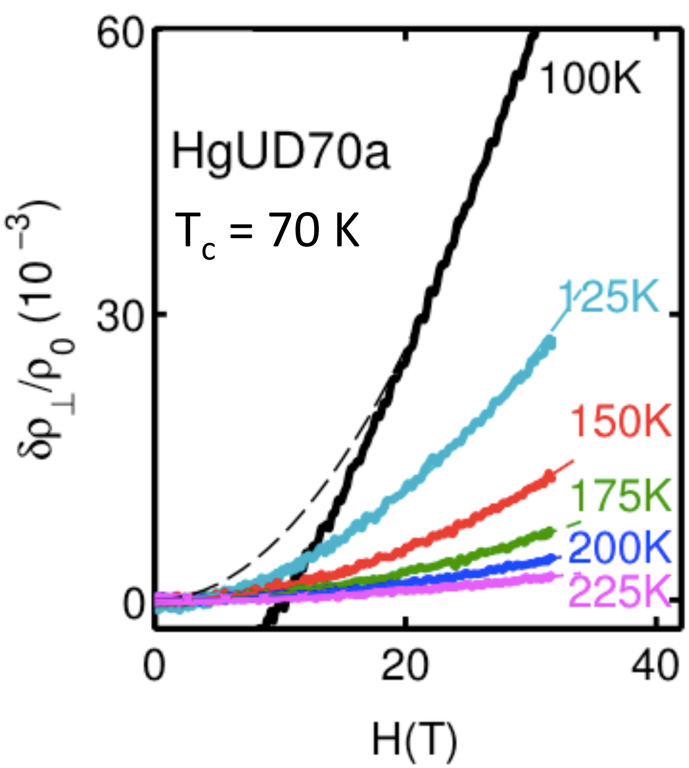




M .K. Chan *et al.* unpublished

Validity of Kohler's rule

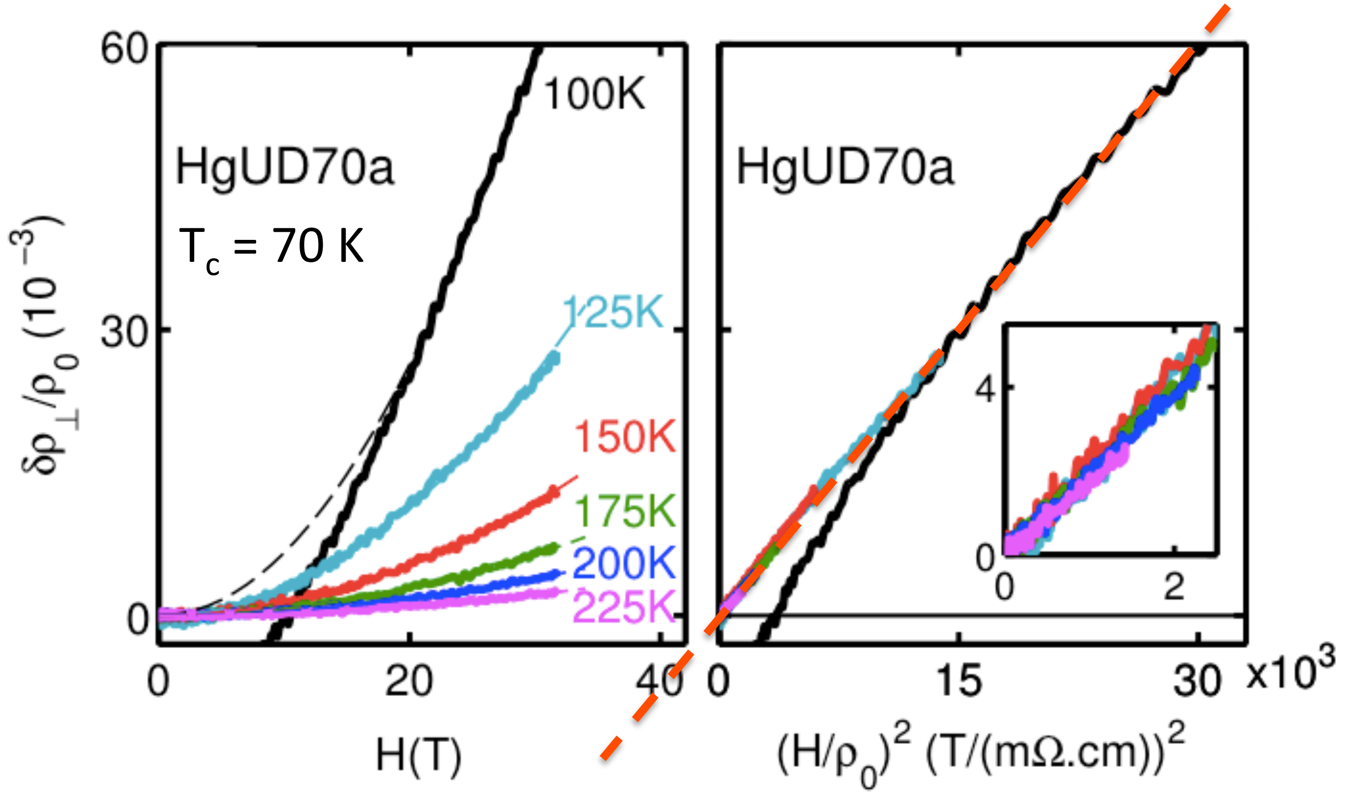
- Pulsed field measurements at LCNMI-Toulouse. 30 T. j // ab; H//c
- $\delta\rho/\rho_0 = a' H^2$



M .K. Chan *et al.* arXiv:1402.4472

Validity of Kohler's rule

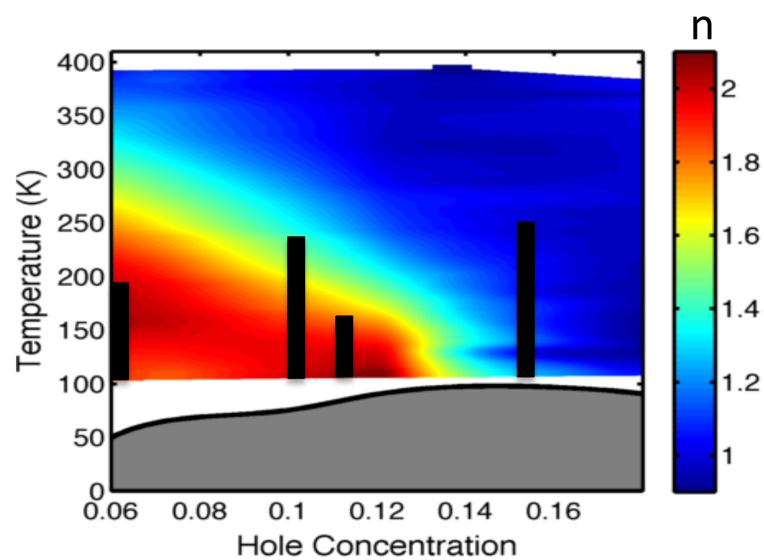
- Pulsed field measurements at LCNMI-Toulouse. 30 T. j // ab; H//c
- $\delta\rho/\rho_0 = a' H^2$
- **Kohler's rule is valid in the pseudogap**

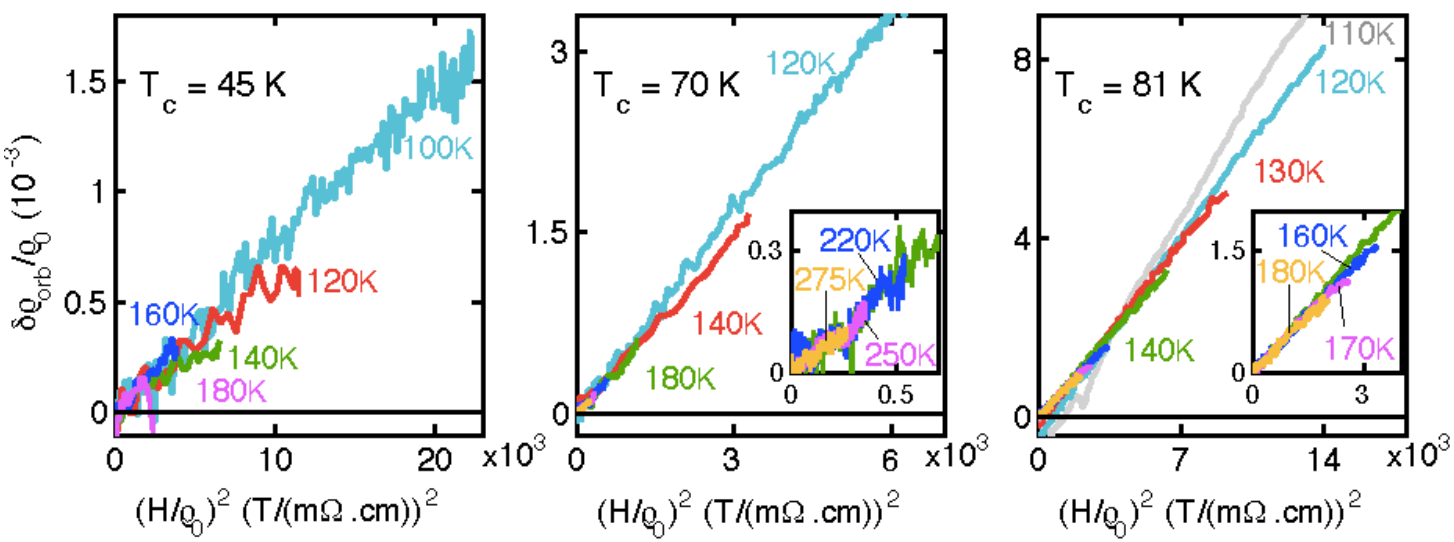


M .K. Chan *et al.* arXiv:1402.4472

Doping dependence of Kohler's rule

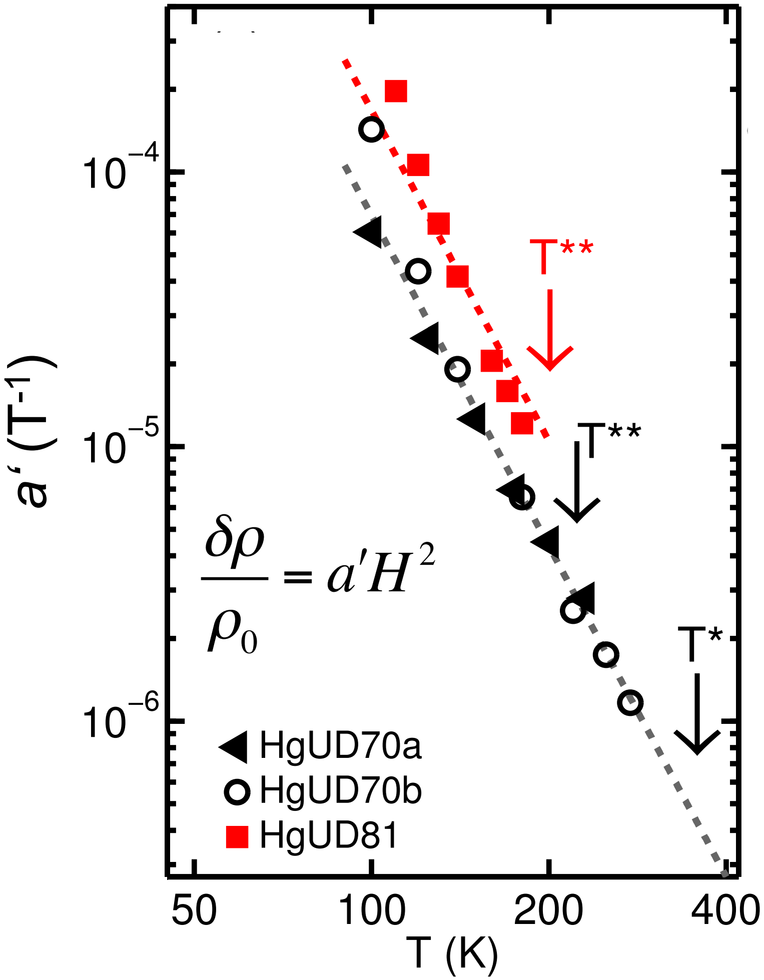
- In-house measurements : H = 9 Tesla
- Kohler's rule valid throughout pseudogap regime where $\rho \sim T^2$
- Kohler's rule broken in the strange-metal regime: $\rho \sim T^1$





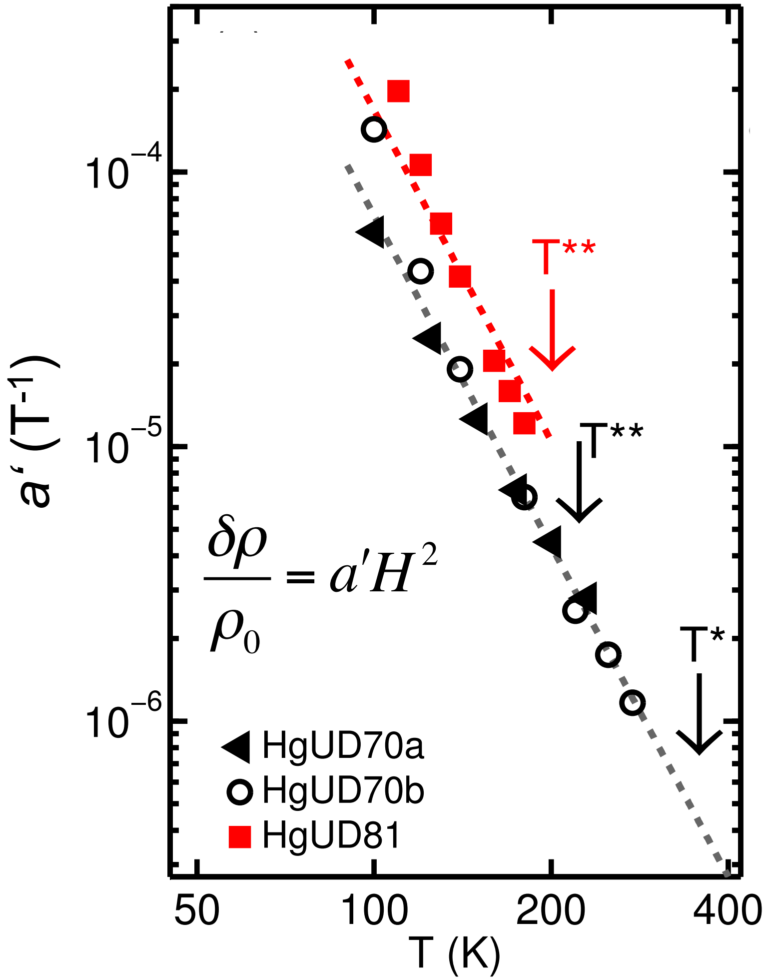
Temperature dependence of MR

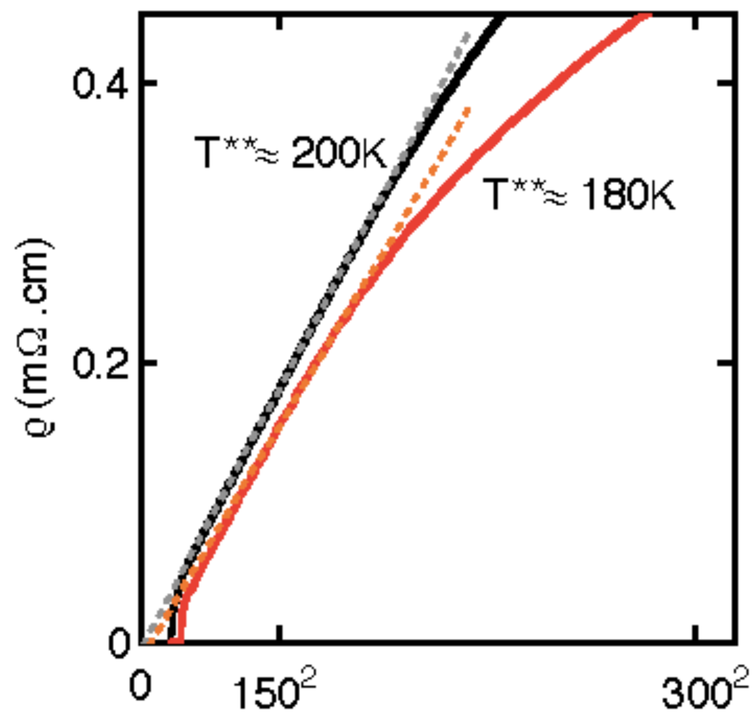
$$\frac{\delta\rho}{\rho_0} \propto (H\tau)^2 \propto T^{-4}$$



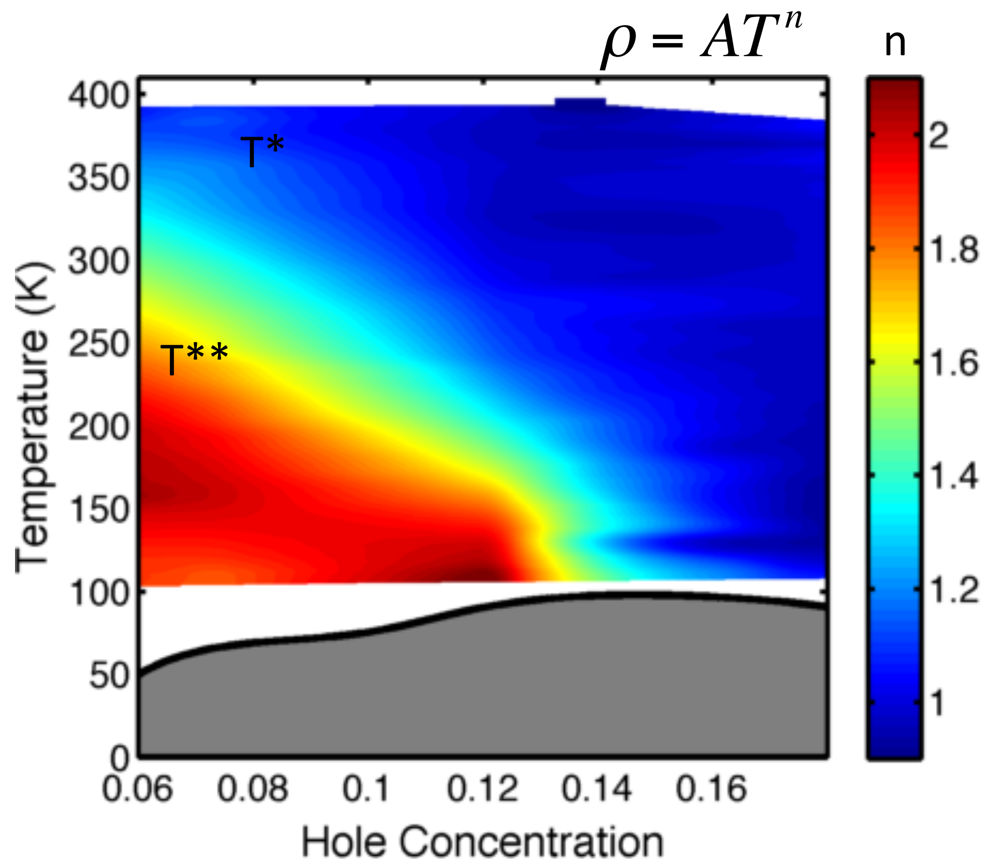
Temperature dependence of MR

$$\boxed{\frac{\delta\rho}{\rho_0} \propto (H\tau)^2 \propto T^{-4}} + \boxed{\rho \propto (1/\tau) \propto T^2} = \boxed{\text{Kohler's rule}}$$



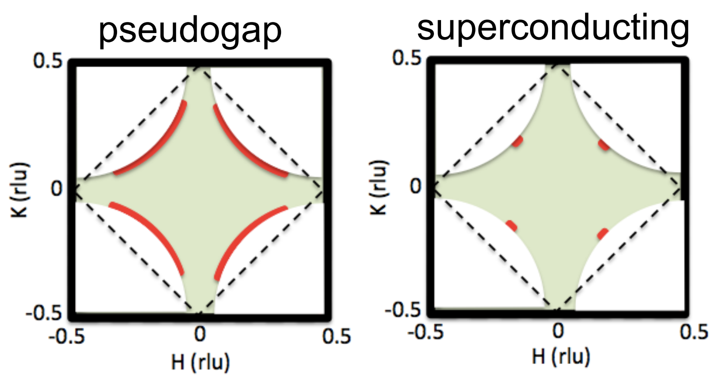


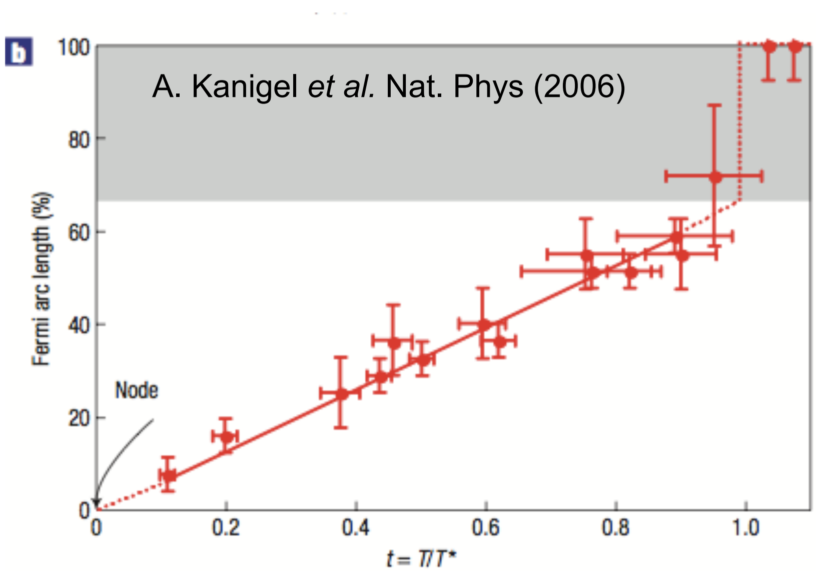
Implications

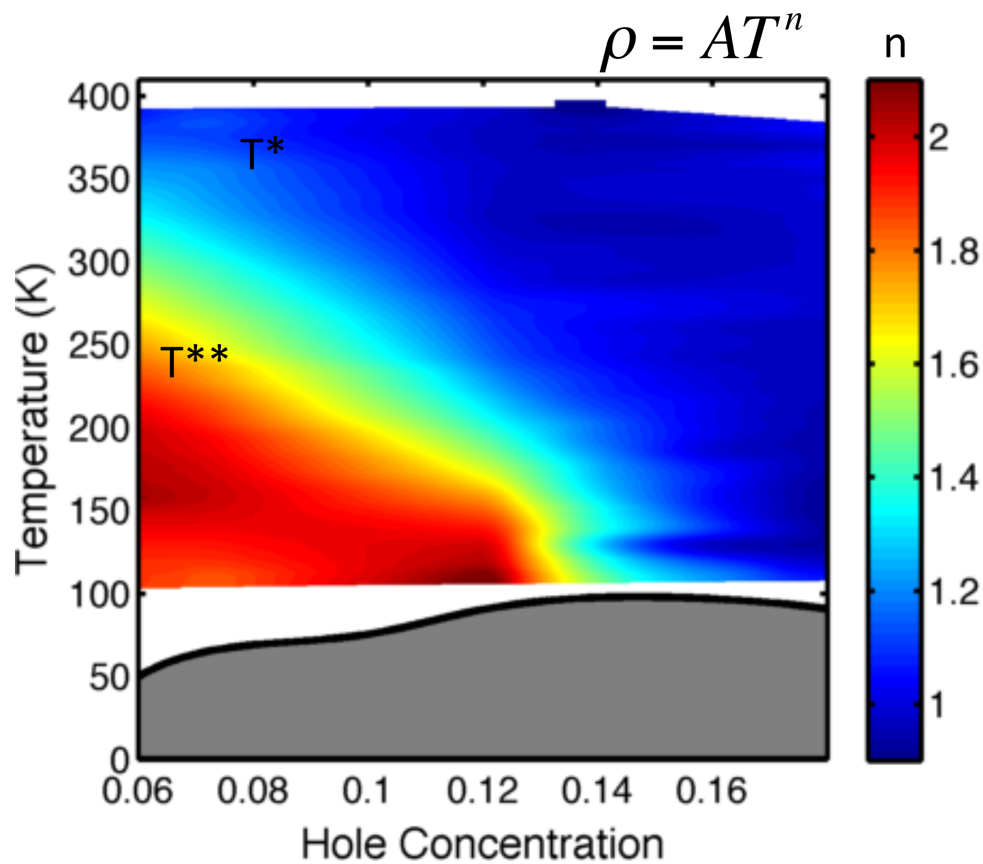


- Only one Fermi-liquid-like scattering rate
- Constant carrier density
- Stable Fermi surface between T_c and T**

Implications

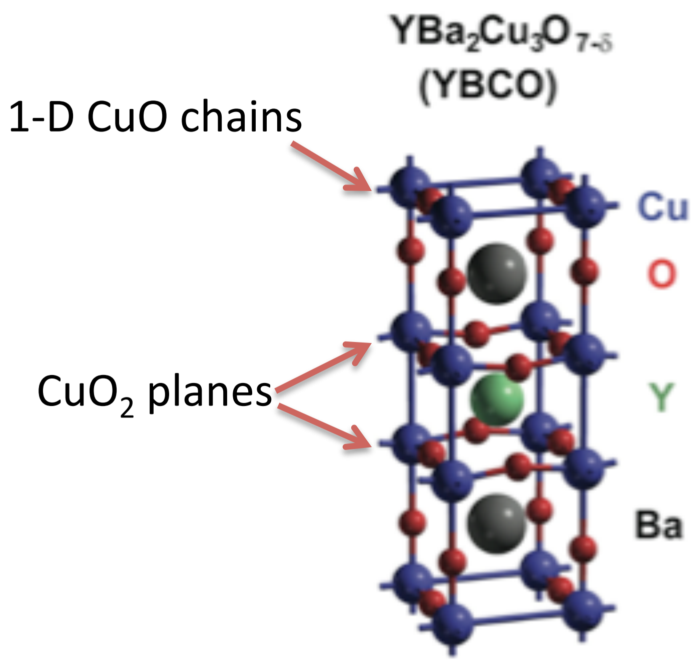


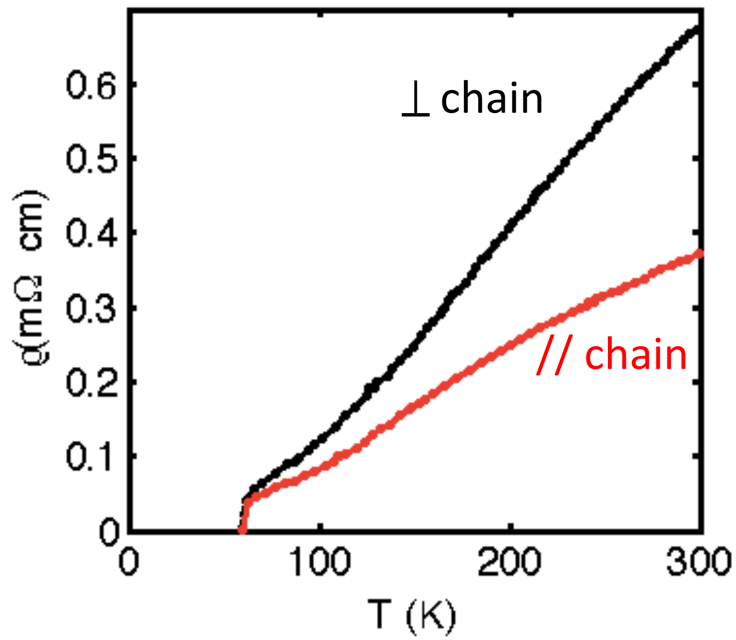




- Pseudogap is not fluctuating superconductivity
- Stable Fermi arc in the pseudogap supported by more recent ARPES results in optimally doped Bi-compounds: T. Kondo *et al.* PRL (2013)

The case of YBCO

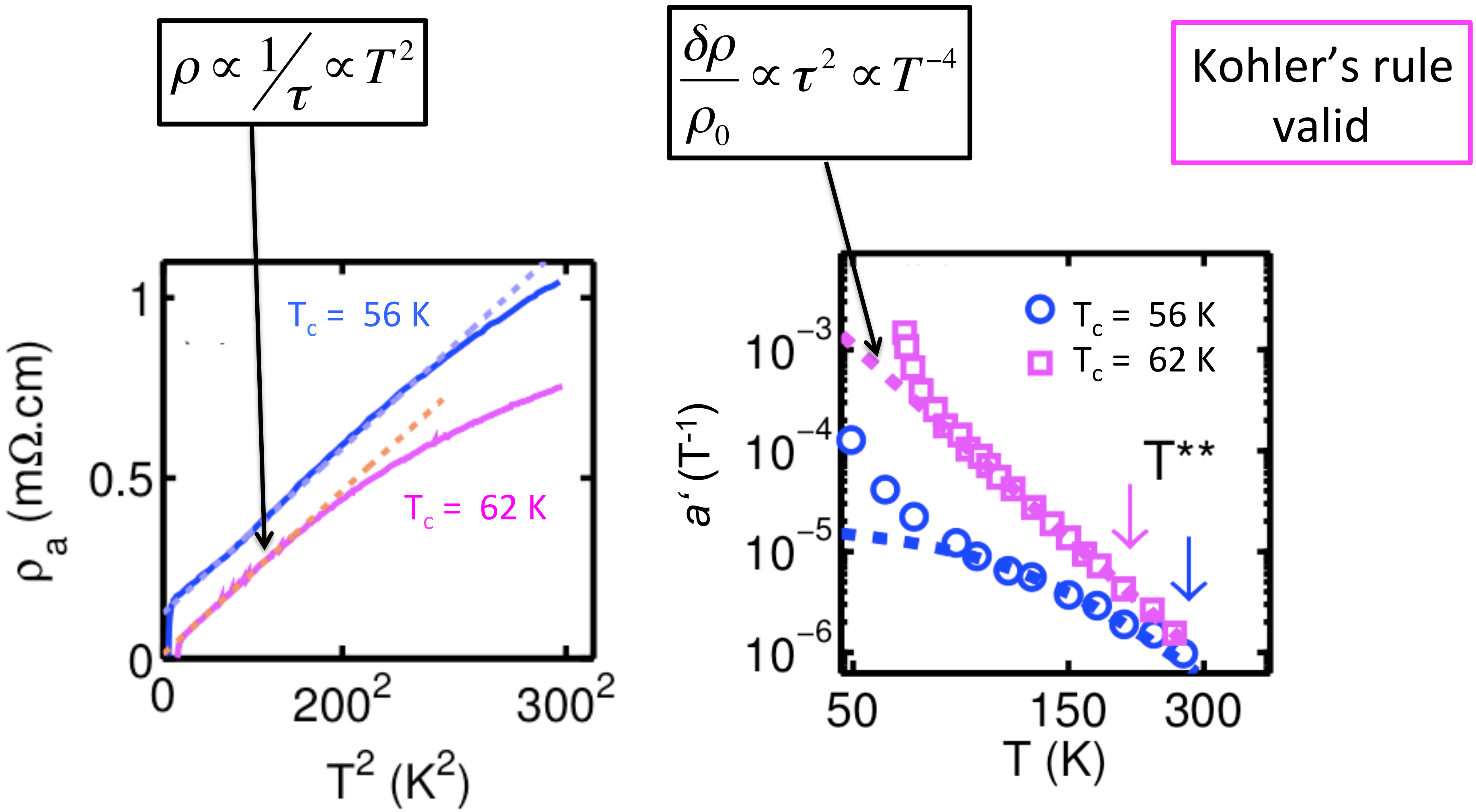




Adapted from Y. Ando *et al.* PRL (2002)

- CuO chains contribute to the electrical transport : measurements in twinned crystals naturally violate Kohler's rule
- Chains shouldn't contribute to the electrical transport transverse to them

Transport perpendicular to CuO chains



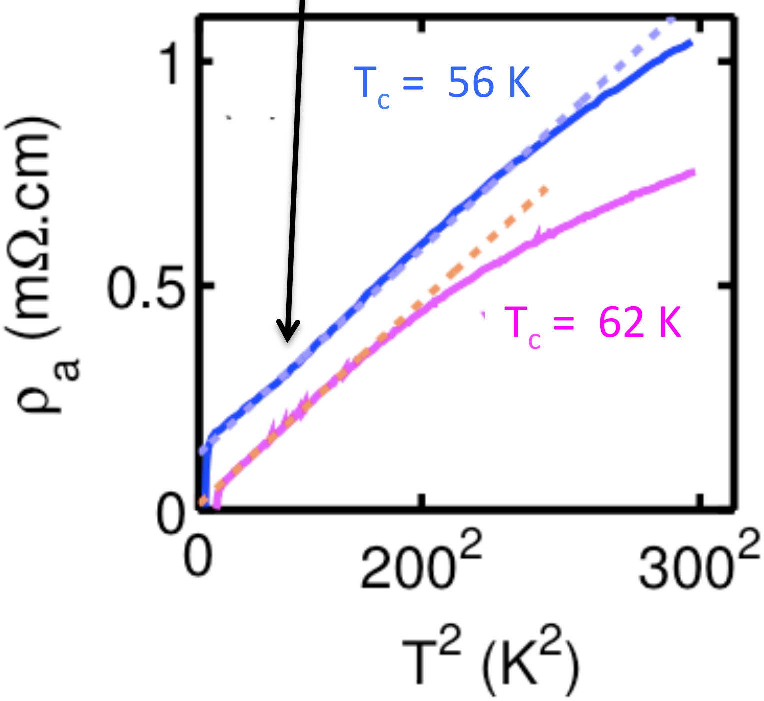
Adapted from Y. Ando *et al.* PRL (2002)

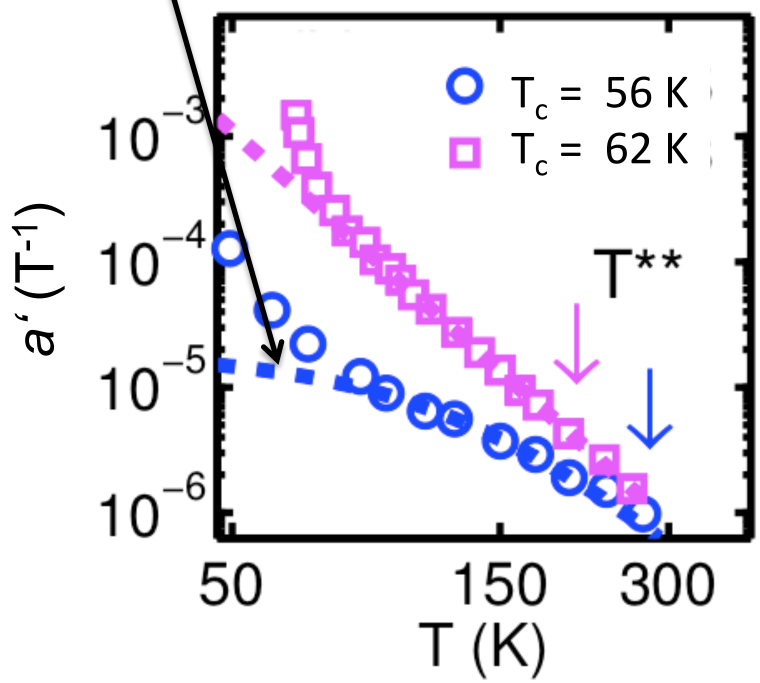
Transport perpendicular to CuO chains

$$\rho \propto 1/\tau = b + cT^2$$

$$\frac{\delta\rho}{\rho_0} \propto \tau^2 = \frac{1}{\left(b + cT^2\right)^2}$$

Kohler's rule
not valid



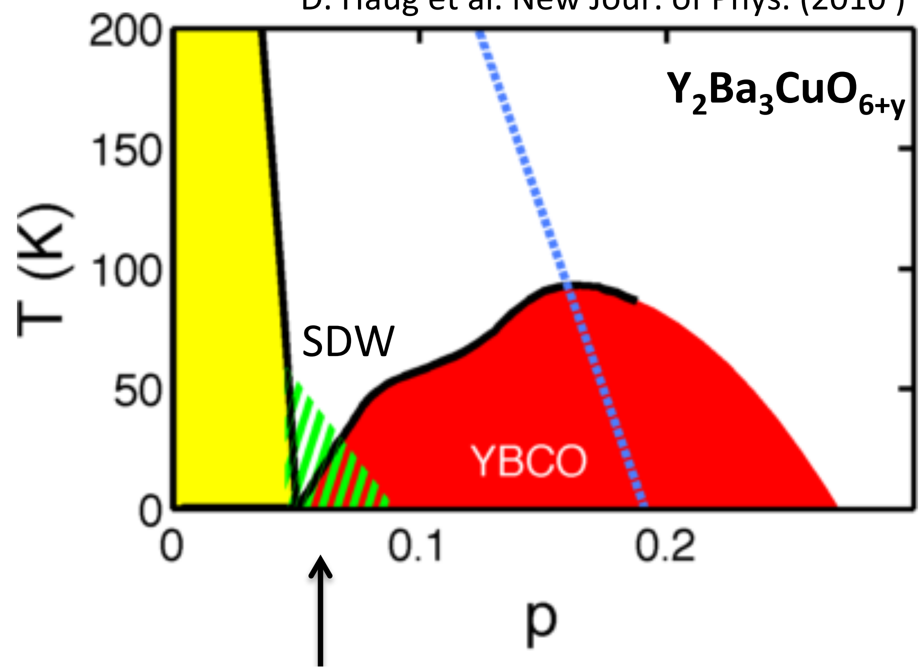


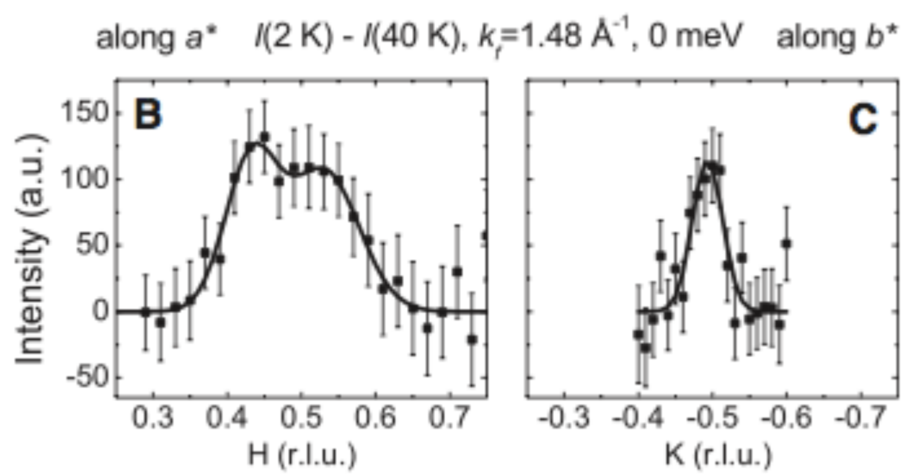
Adapted from Y. Ando *et al.* PRL (2002)

Magnetic phase diagram and residual resistivity

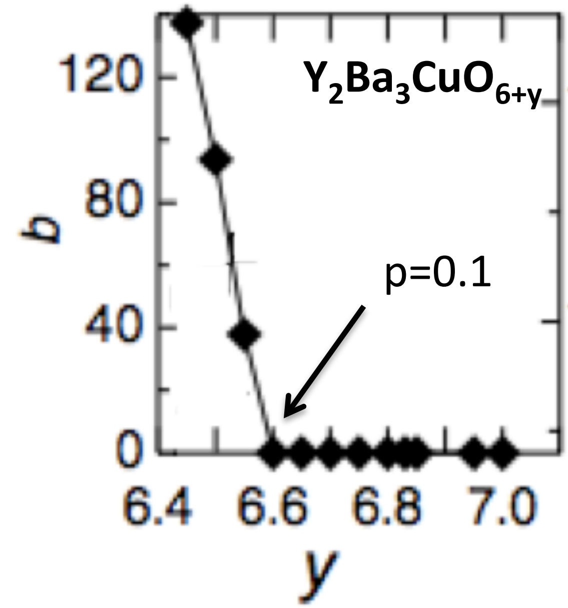
- 3D AF ➔ incommensurate SDW

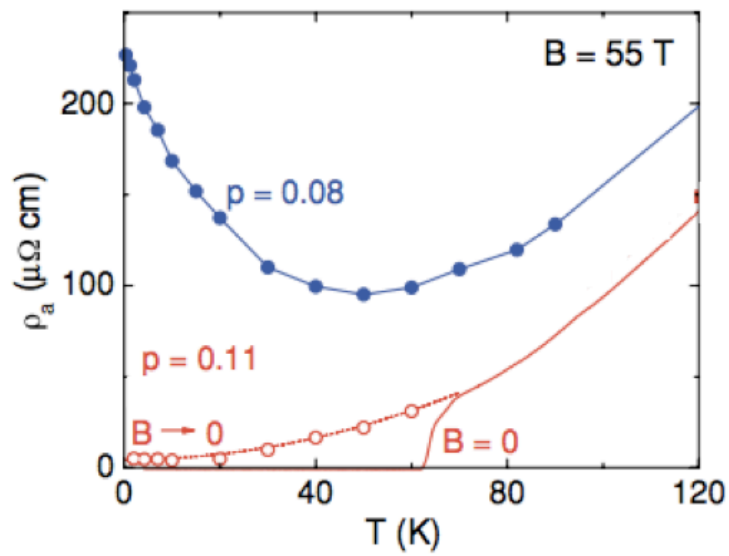
D. Haug et al. New Jour. of Phys. (2010)





Y. Ando et al. PRL (2002)

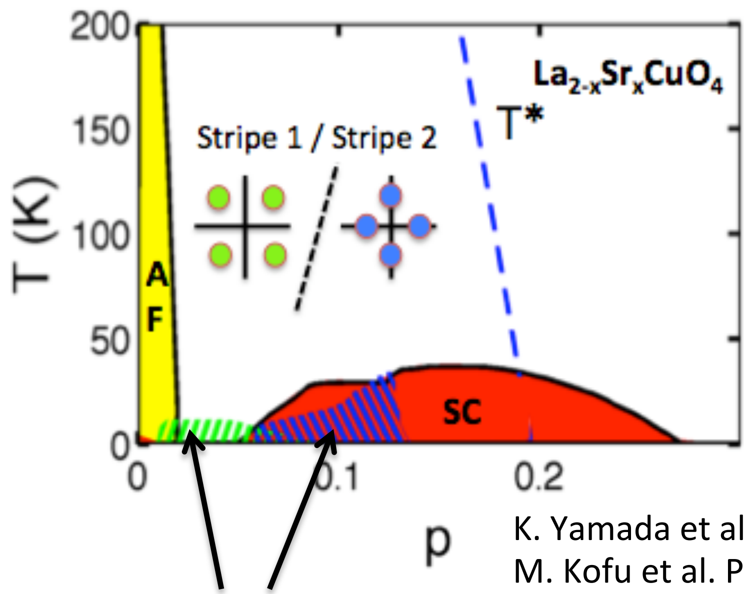




D. LeBoeuf et al. PRB (2011)

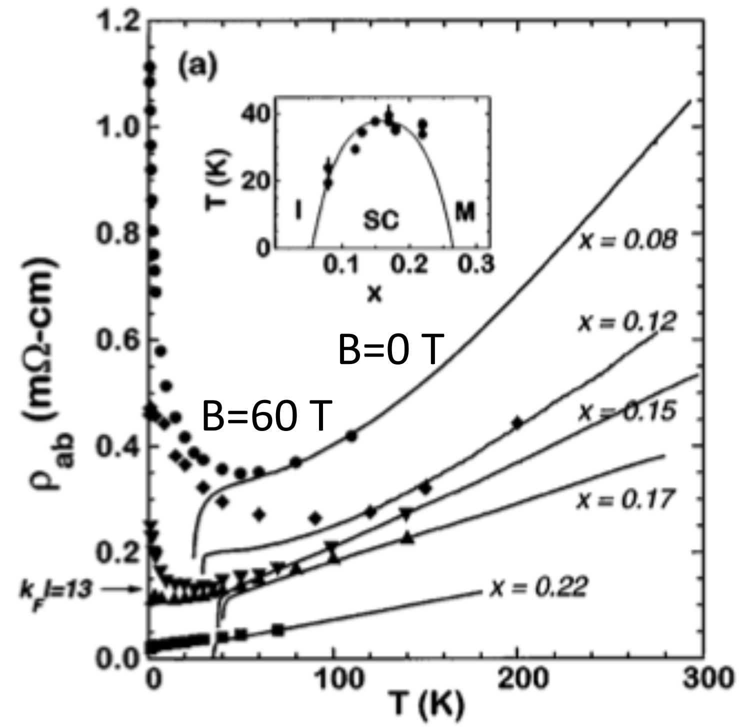
Magnetic phase diagram and residual resistivity

- 3D AF ➔ diagonal incommensurate➔parallel incommensurate



K. Yamada et al. PRB (1998)
M. Kofu et al. PRL (2009)

Local moment physics

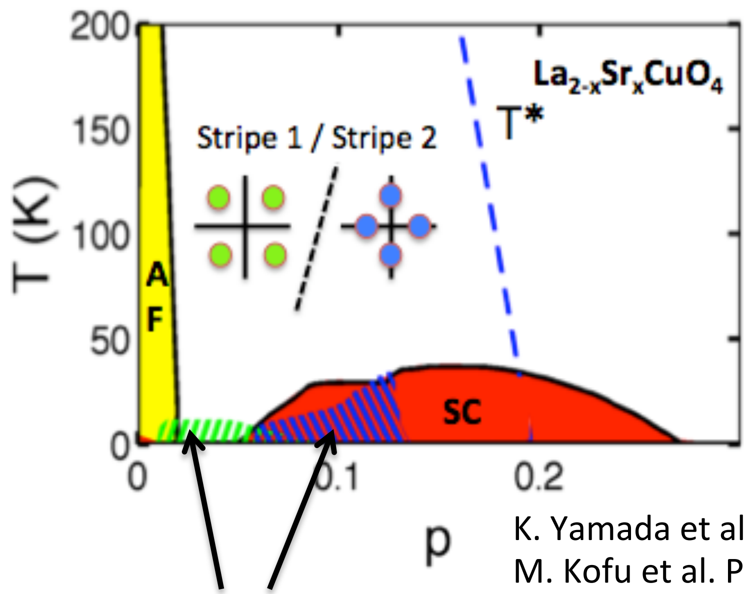


G. S. Boebinger et al. PRL (1996)

- Large residual resistivity is an indicator of carrier localization at low temperatures and quasielastic magnetic ordering

Magnetic phase diagram and residual resistivity

- 3D AF ➔ diagonal incommensurate➔parallel incommensurate



K. Yamada et al. PRB (1998)
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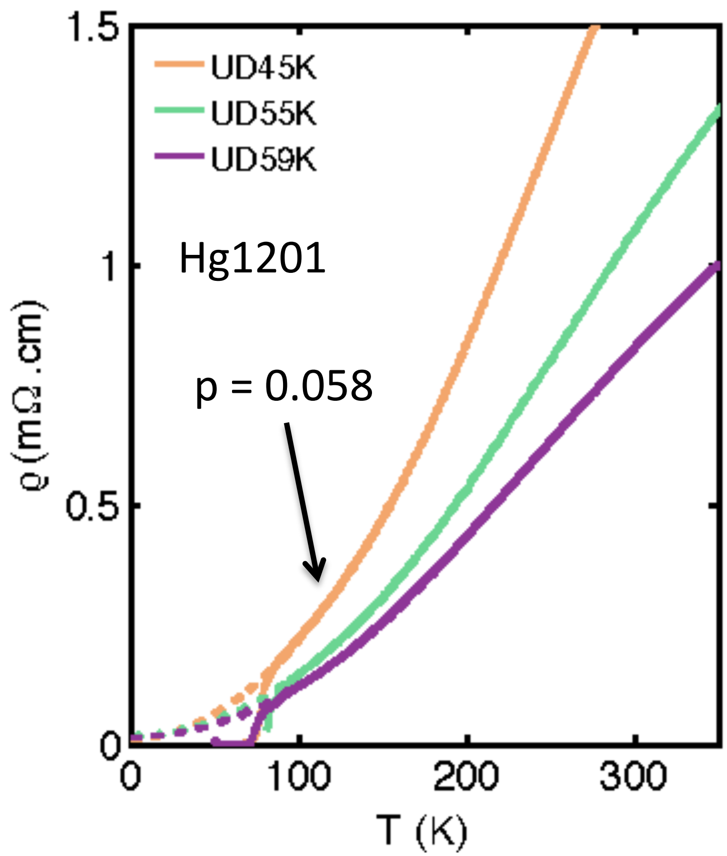
Local moment physics



- p_{MI} (LSCO) ≈ .17
- p_{MI} (YBCO) ≈ .10
- p_{MI} (Hg1201) < 0.058
- Quantum oscillations in p=0.09 (N. Barišić *et al.* Nature Phys. (2013))

Part 2: Inelastic Neutron scattering

Part 2: Inelastic Neutron scattering

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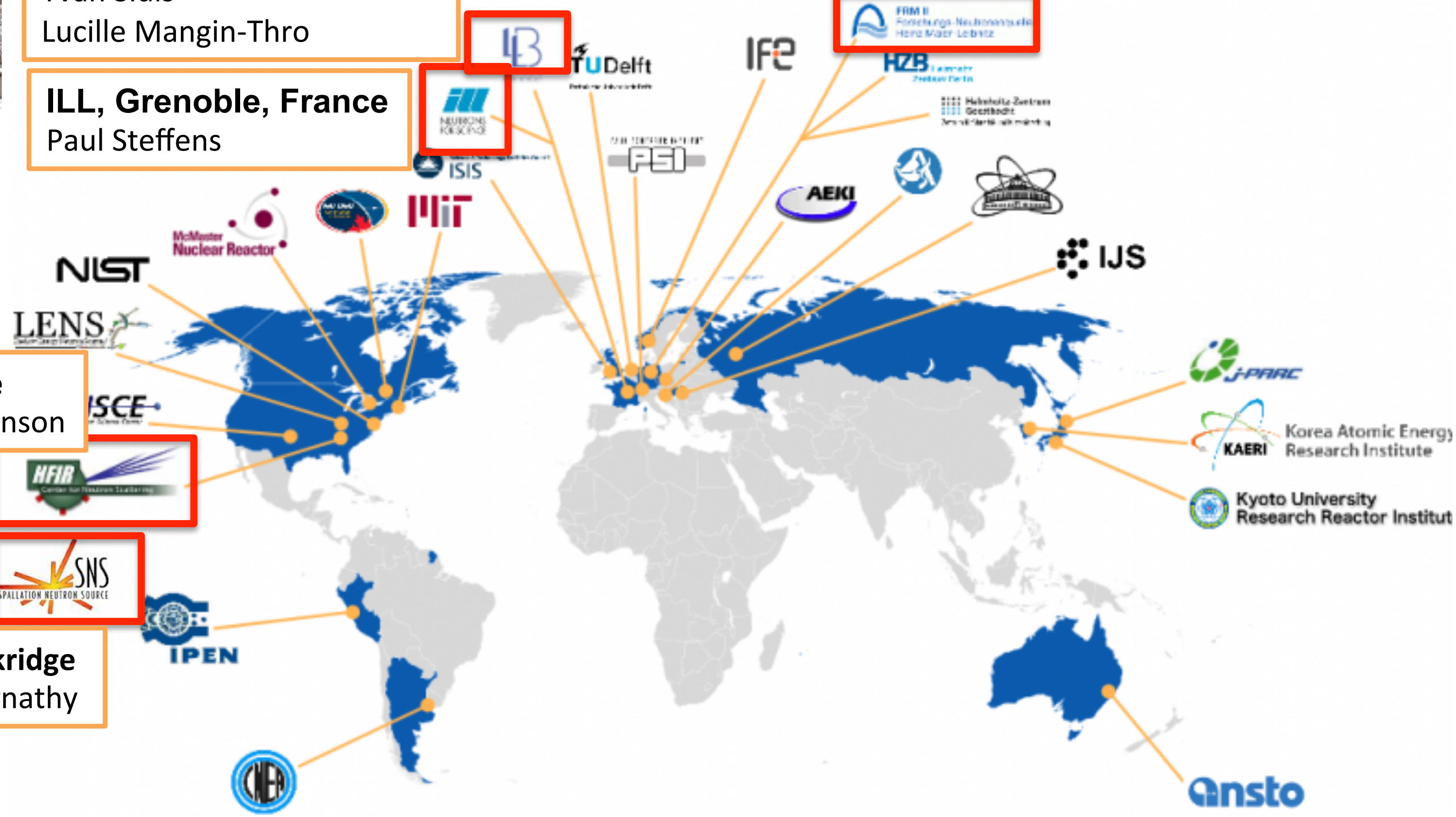
Philippe Bourges
Yvan Sidis
Lucille Mangin-Thro

ILL, Grenoble, France
Paul Steffens

FRM-II, Garching, Germany
Jitae Park

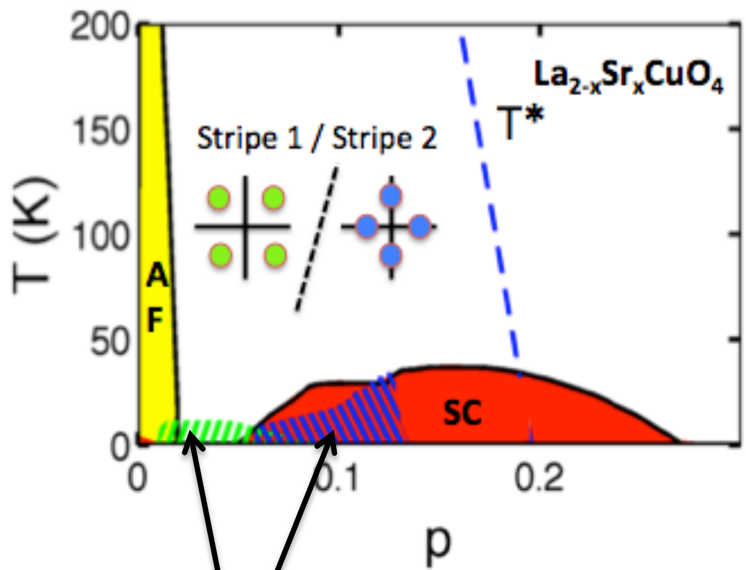
ORNL, Oakridge
Andrew Christianson

ORNL, Oakridge
Doug Abernathy

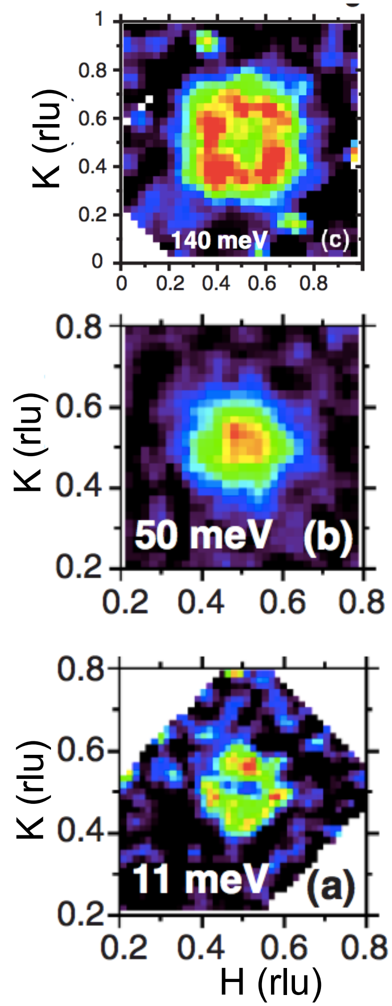


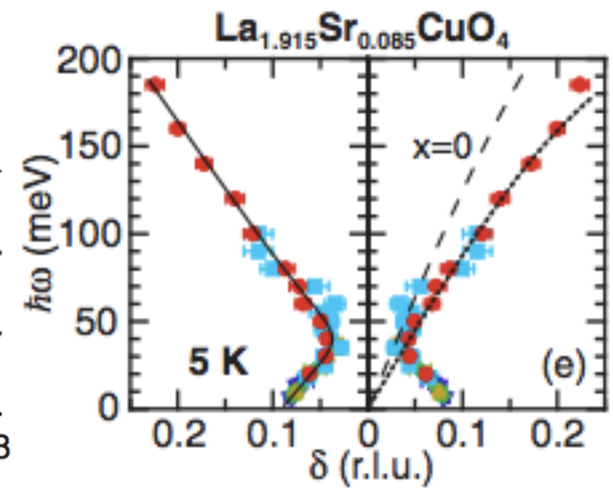
Magnetic phase diagram

- **3D AF ➔ diagonal incommensurate➔parallel incommensurate**



Local moment physics



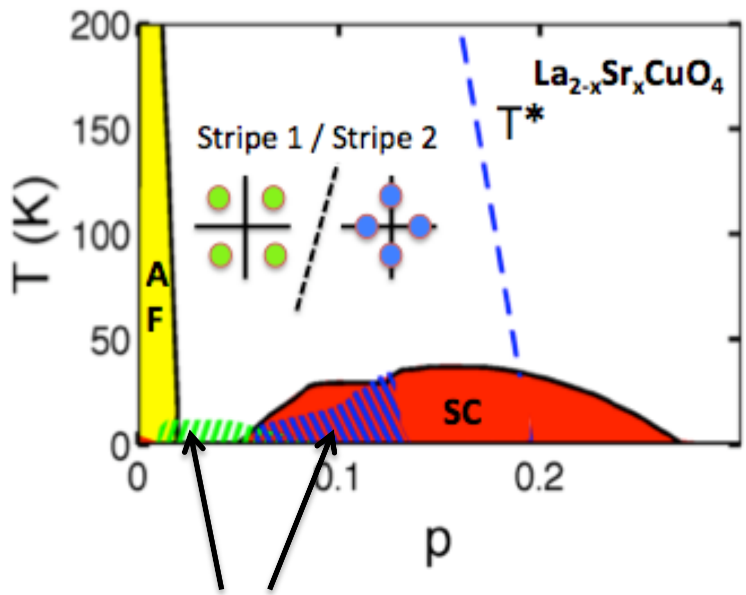


(½, ½)

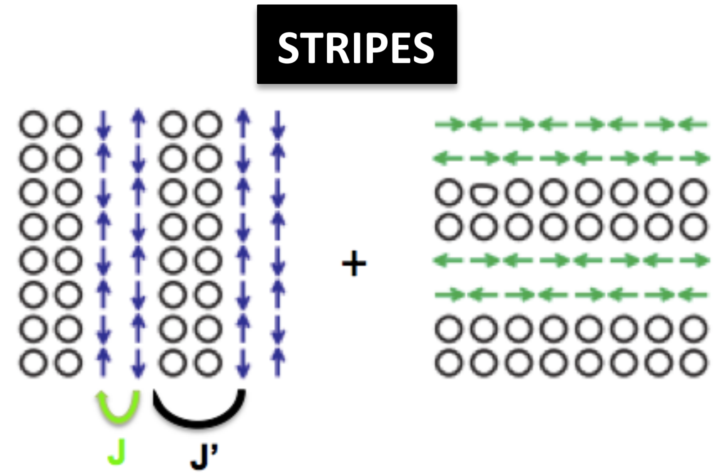
O.J. Lipscombe *et. al,* PRL (2009)

Magnetic phase diagram

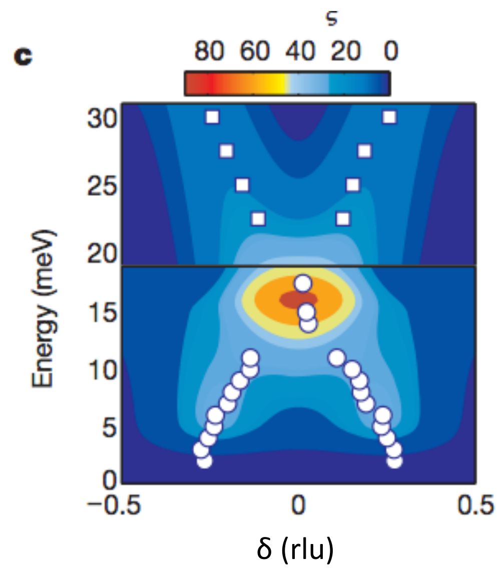
- **3D AF ➔ diagonal incommensurate➔parallel incommensurate**



Local moment physics



J. M. Tranquada et al. Nature 429 534 (2004)

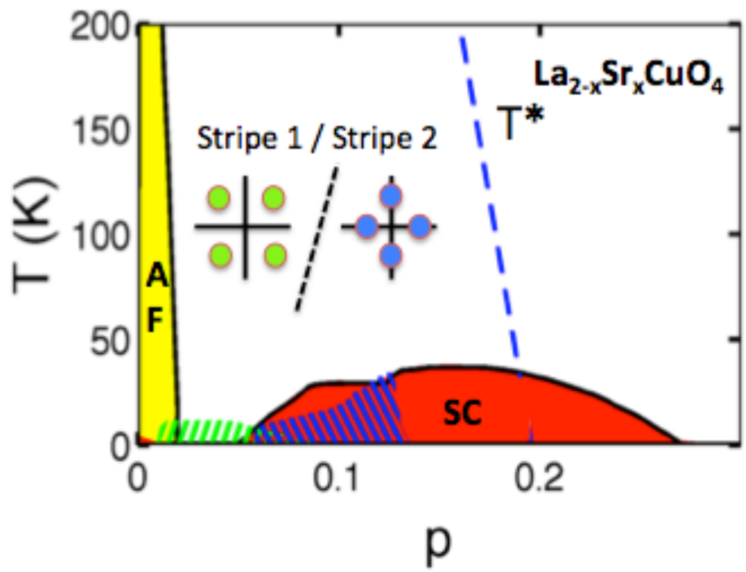


Stripe-ordered $La_{5/3}Sr_{1/3}CoO_4$

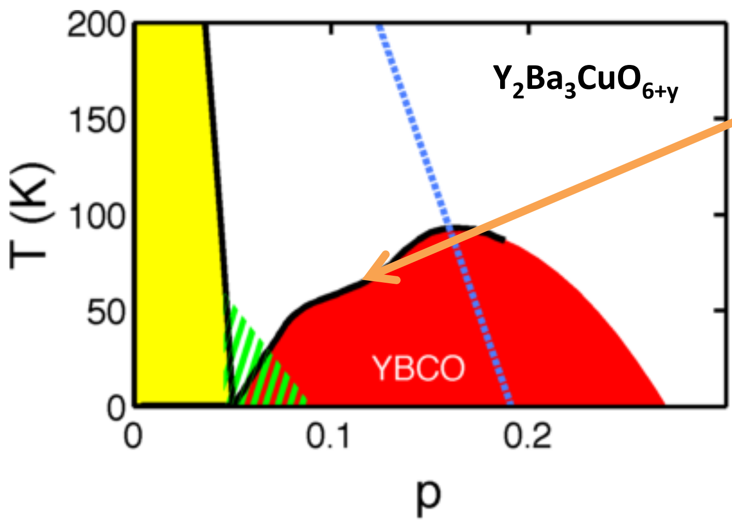
A. T. Boothroyd *et al.* Nature (2011)

Magnetic phase diagram

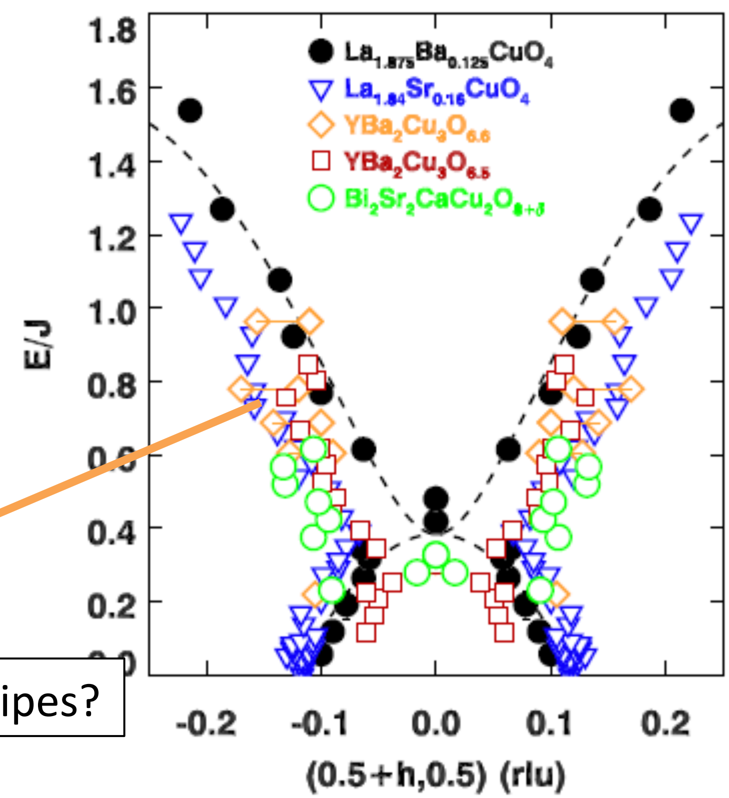
- 3D AF ➔ diagonal incommensurate➔parallel incommensurate



- 3D AF ➔ anisotropic incommensurate➔?

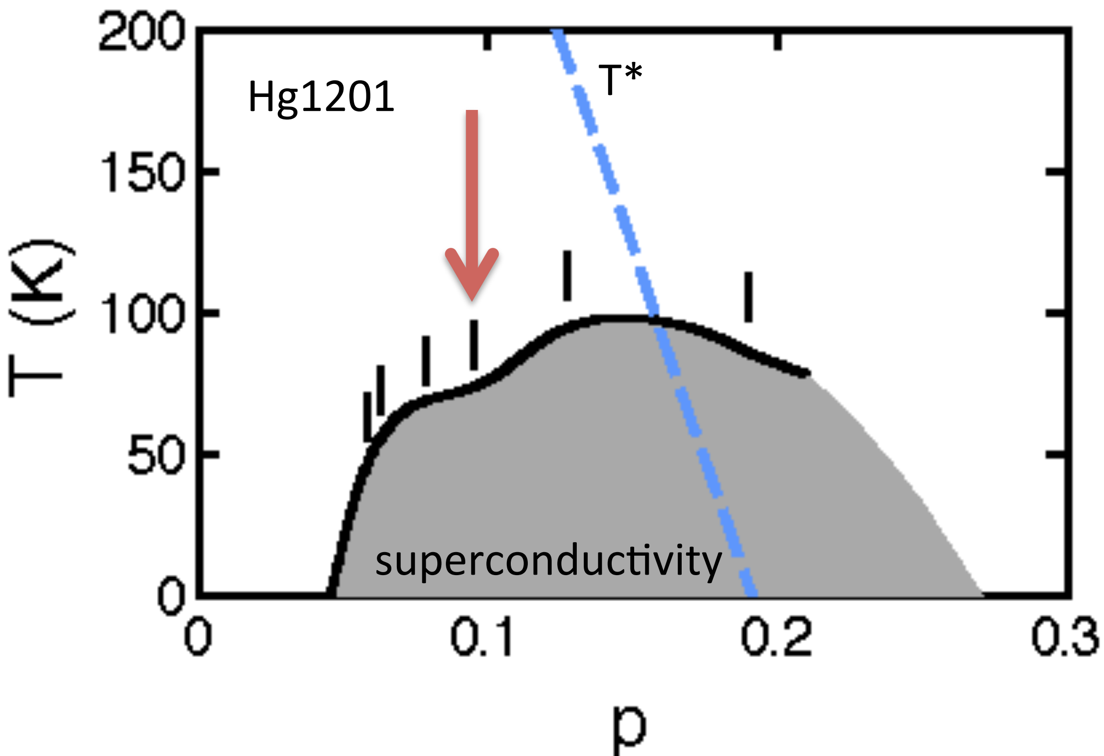


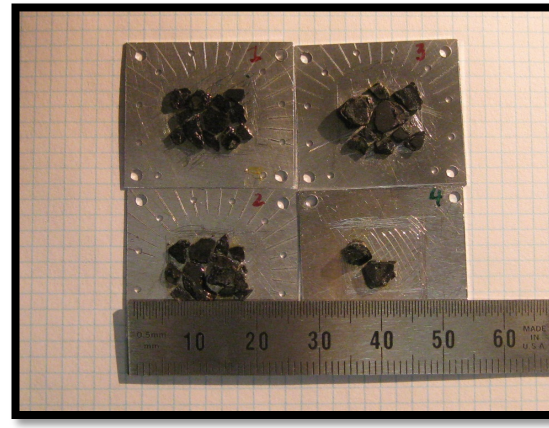
Fluctuating stripes?

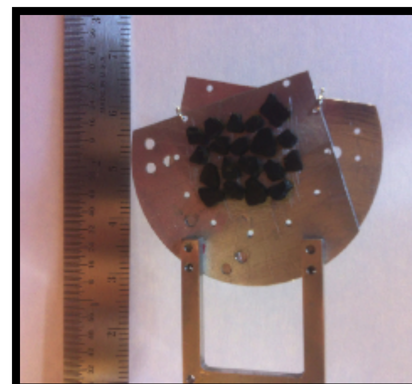


M. Fujita *et al.* Physica C (2012)

Preparing a neutron sample







Each neutron sample:

- ~ 40 growths
- ~30 crystals, ranging from 20 mg – 100 mg each
- 2 – 3 months anneal
- 2 g total mass

Antiferromagnetic Fluctuations

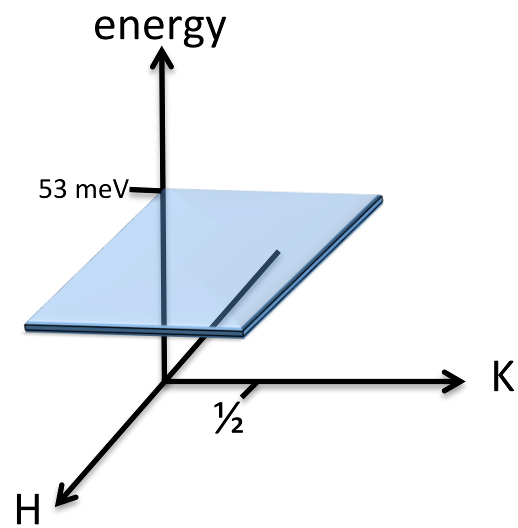
$$\boxed{\frac{d^2\sigma}{d\Omega dE}} = \frac{2(\gamma r_e)^2}{\pi g^2 \mu_B^2} \frac{k_f}{k_i} |F(\mathbf{Q})|^2 \frac{\chi''(\mathbf{Q},\omega)}{1 - \exp(-\omega/k_B T)}$$

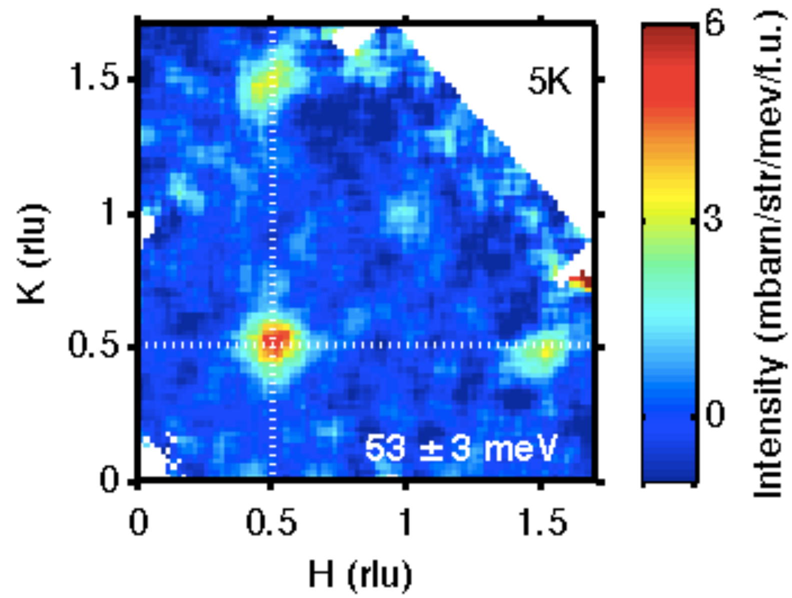
$|F(\mathbf{Q})| = \text{Form Factor}$

$\frac{1}{1-\exp(-\omega/k_B T)}$ = Bose factor

$\chi''(\mathbf{Q},\omega) = $ Imaginary magnetic susceptibility

k_i, k_f = incident and final momenta





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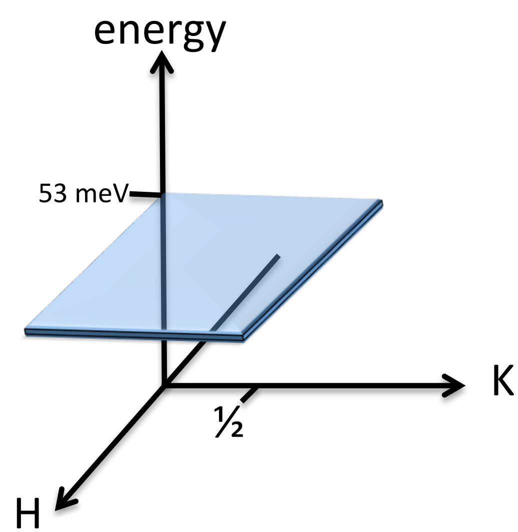

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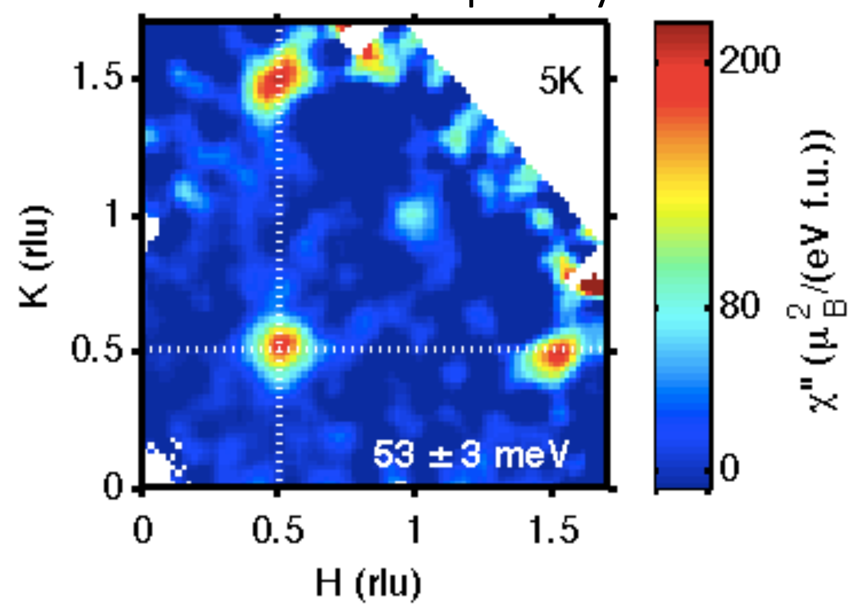
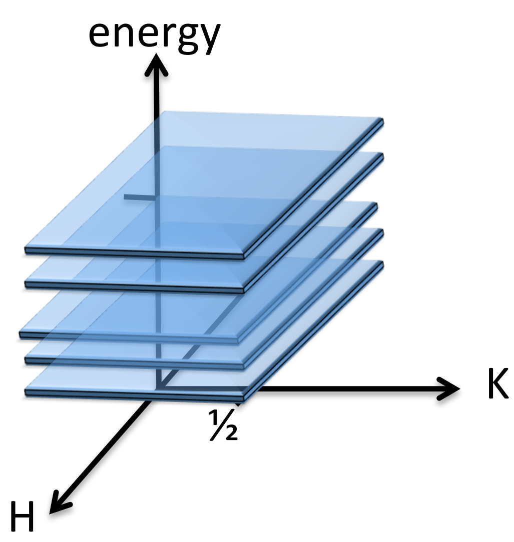
Convert to susceptibility



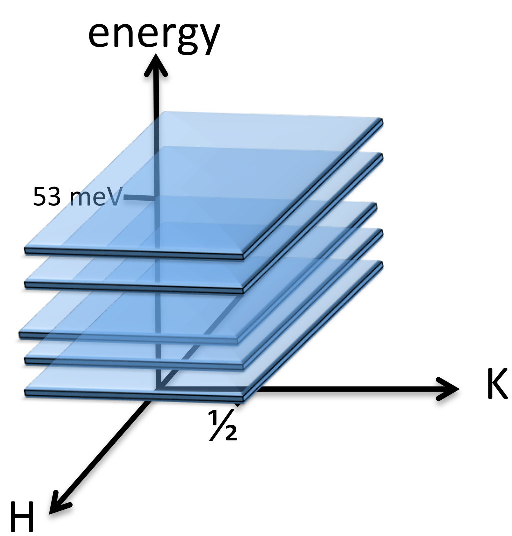
Antiferromagnetic spectrum

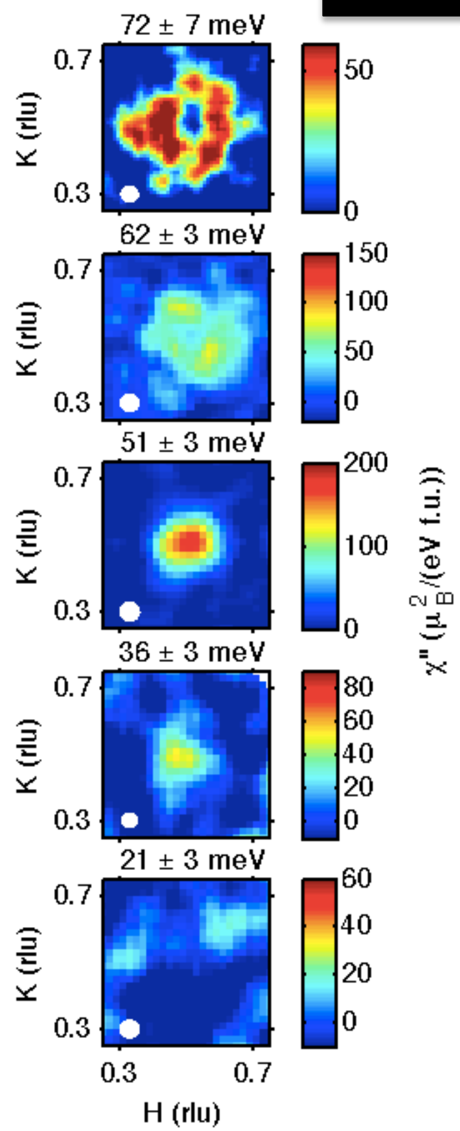


Antiferromagnetic spectrum

- Constant energy images: reveals the Q-structure: commensurate at low energies, ring-like at high energies

T << T_c





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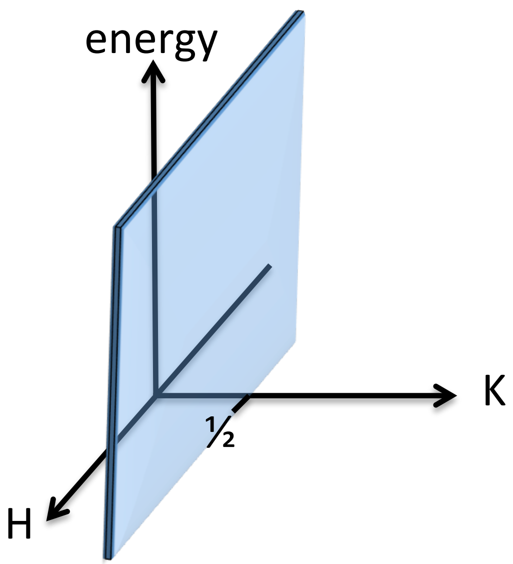

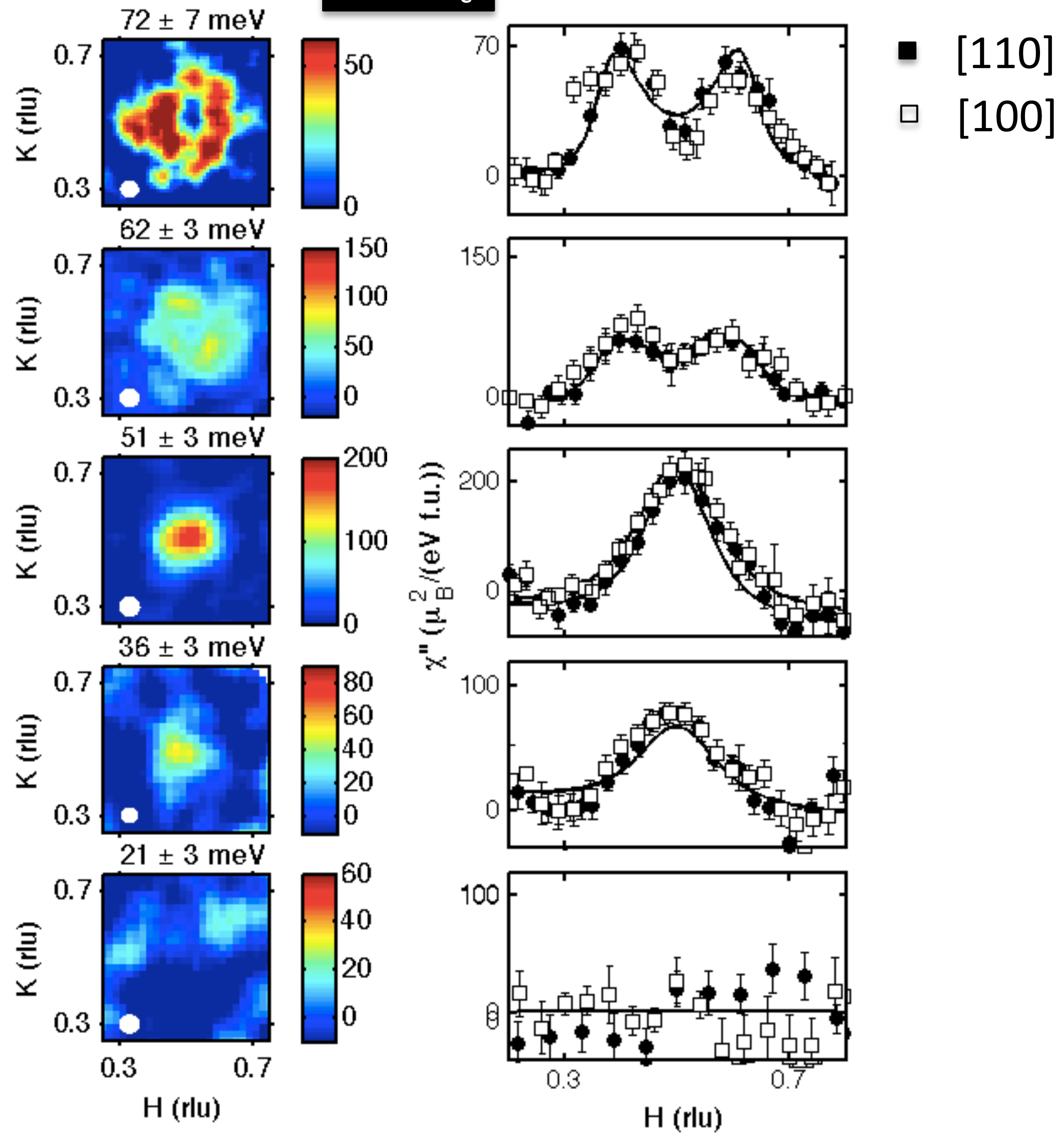

M.K. Chan *et al.* arXiv:1402.4517

Antiferromagnetic spectrum

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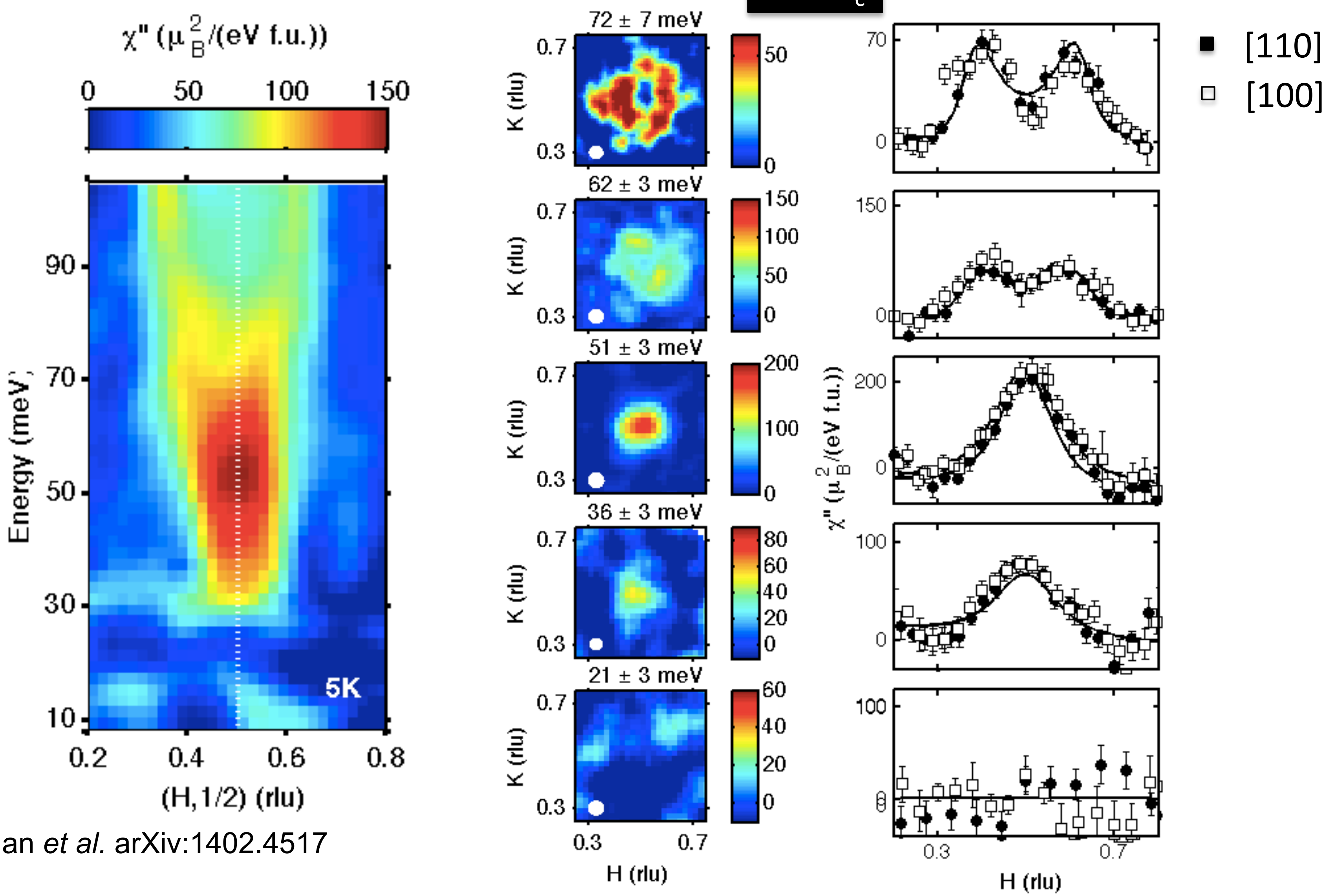
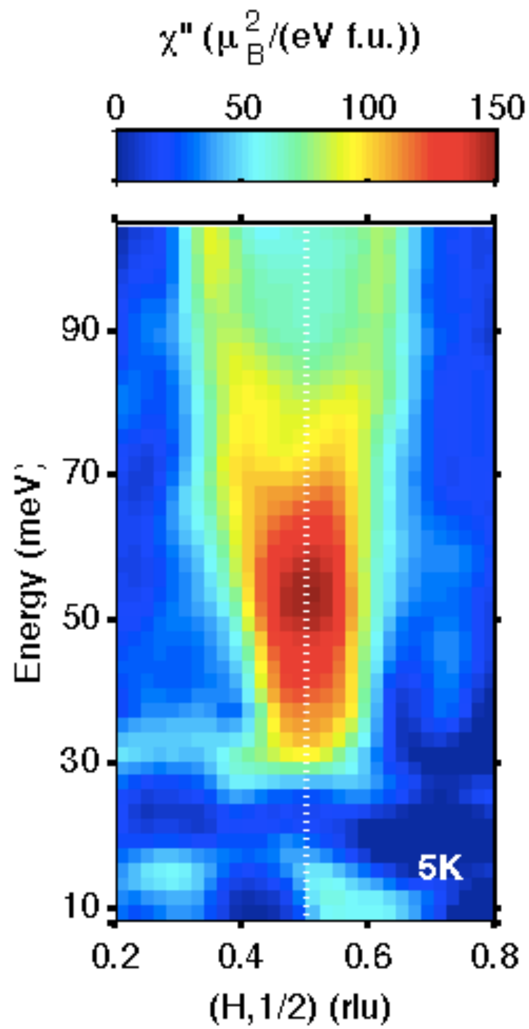


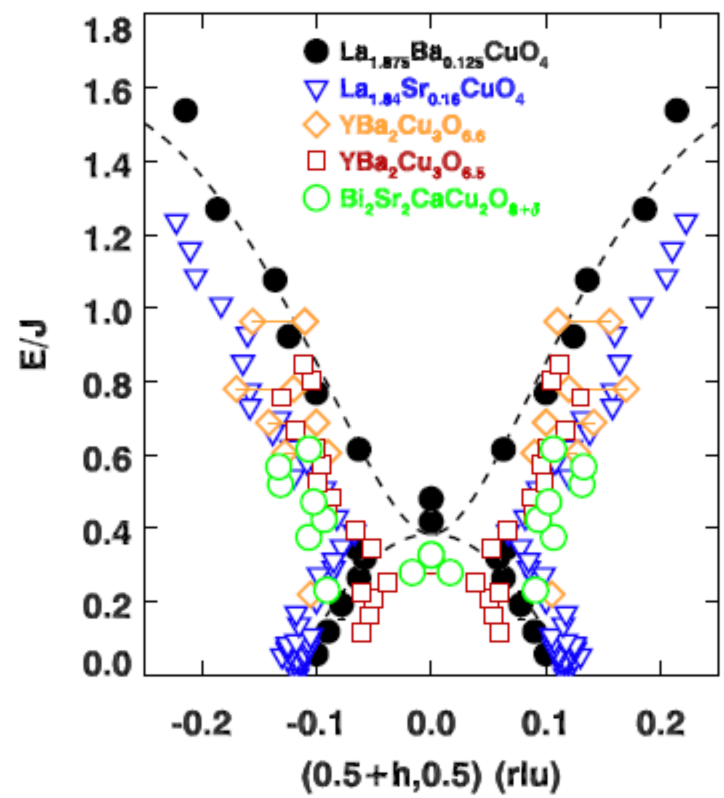
M.K. Chan *et al.* arXiv:1402.4517

Antiferromagnetic spectrum

- ‘Y’- shaped dispersion with 27 meV gap



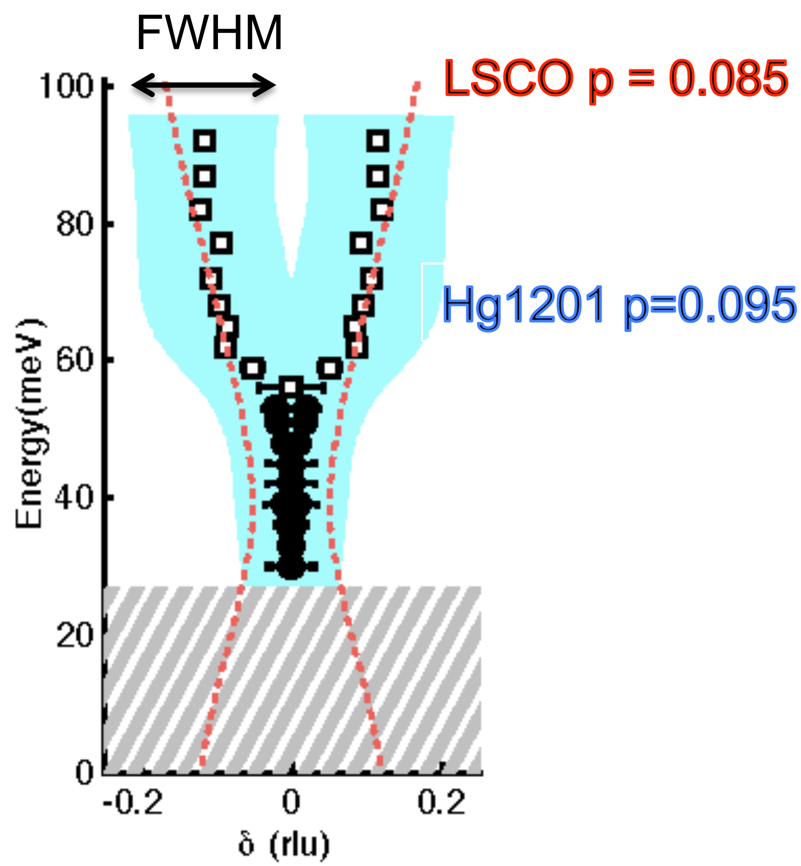
M.K. Chan *et al.* arXiv:1402.4517



M. Fujita *et al.* Physica C (2012)

Compare to LSCO

- Gaped vs ungaped
- Low energy commensurate vs incommensurate dispersion
- Stripe correlations, if present would have to be very weak



O. J. Lipscombe, *et al.* PRL (2009)

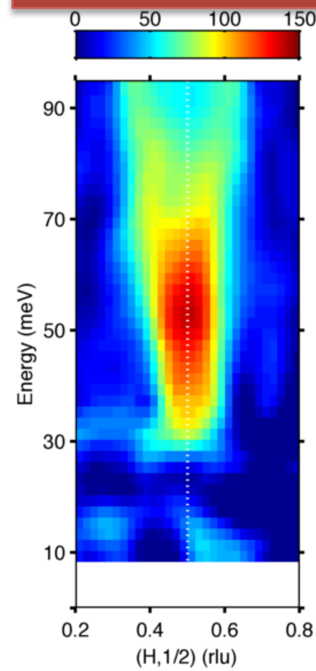
Doping dependence

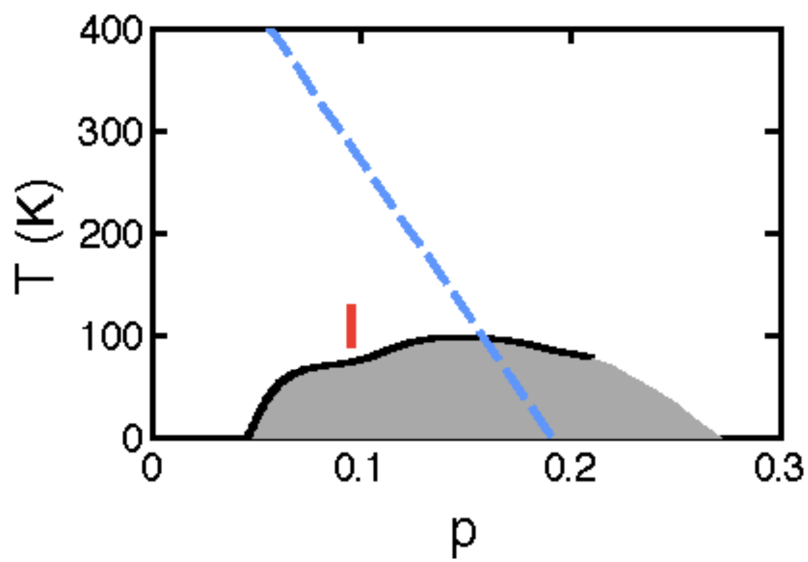
T_c = 55 K; p ≈ 0.063

T_c = 71 K; p ≈ 0.095

T_c = 88 K; p ≈ 0.117

T = 5 K

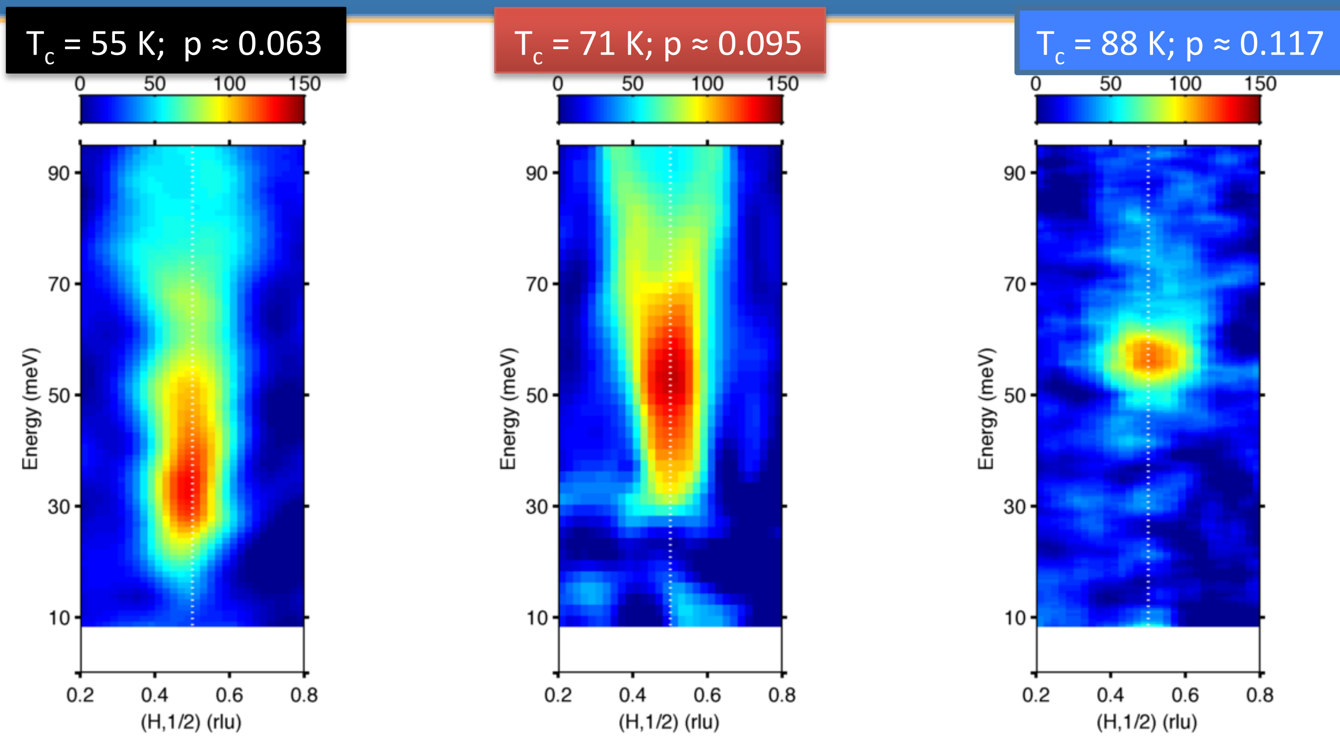


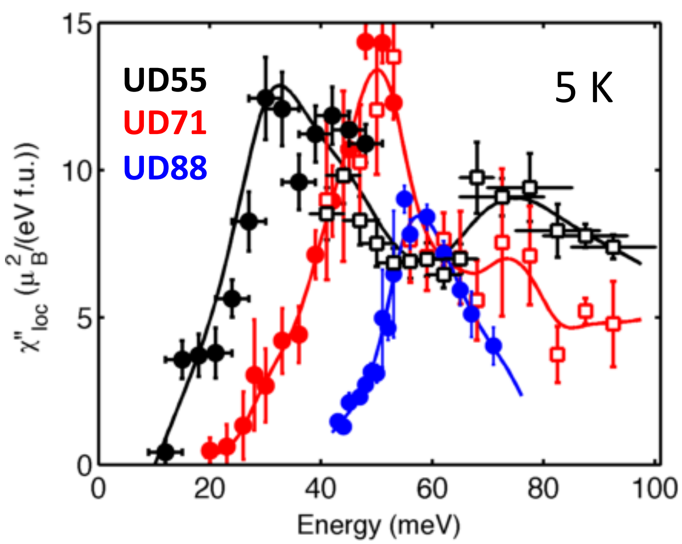


M. K. Chan *et al.* unpublished

Doping dependence

T = 5 K

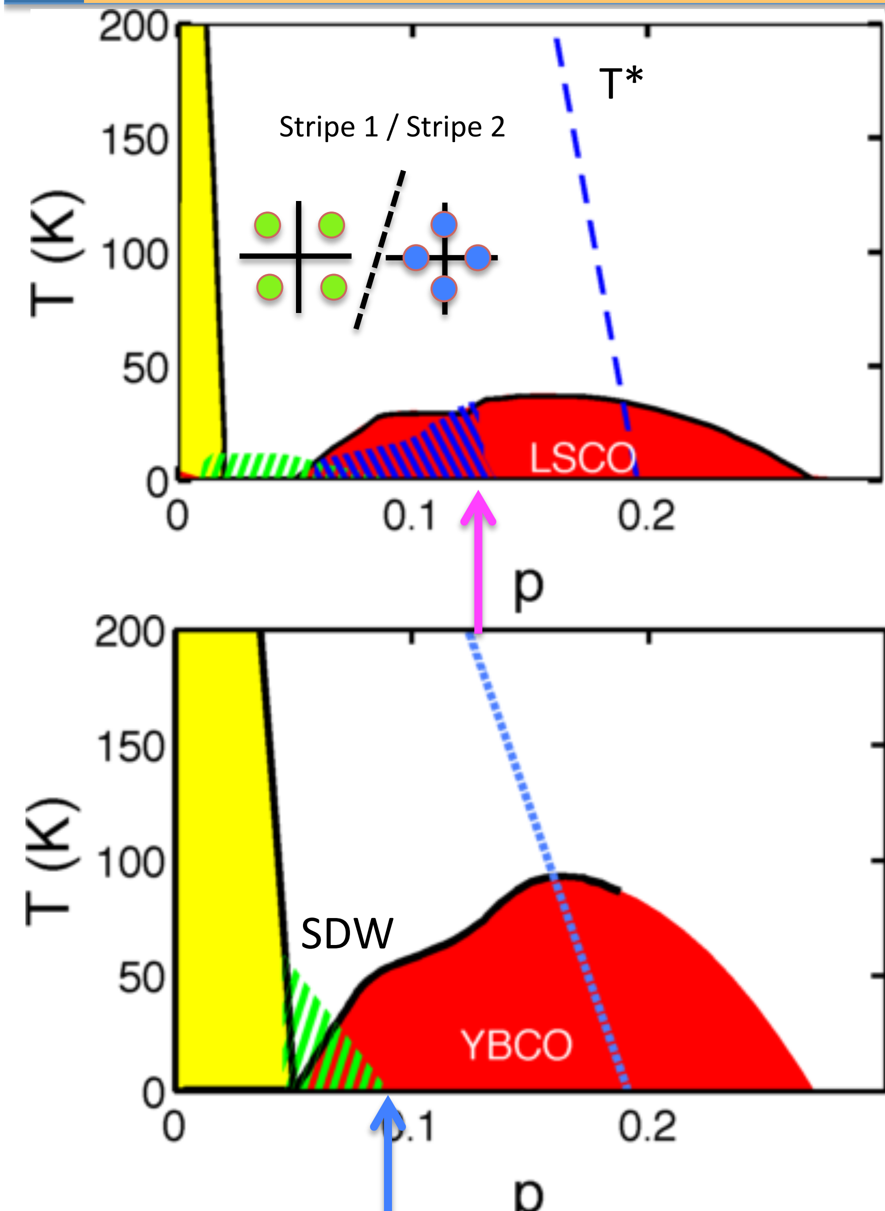


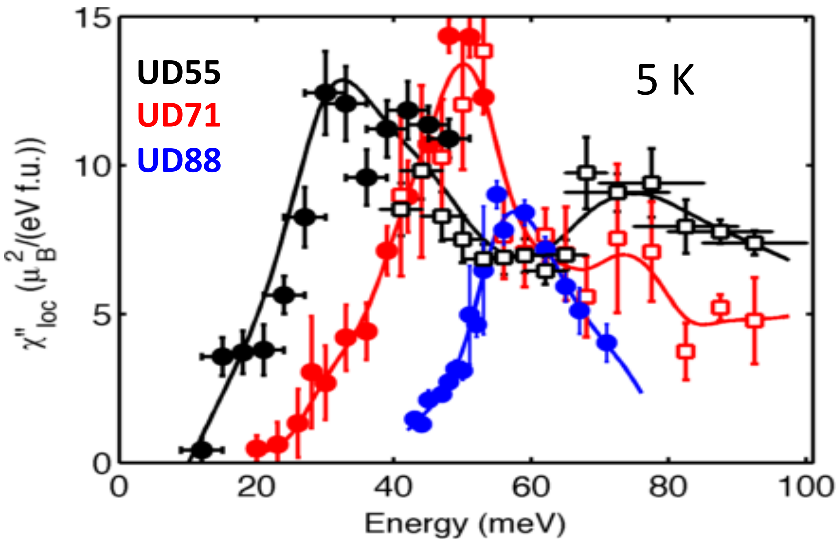


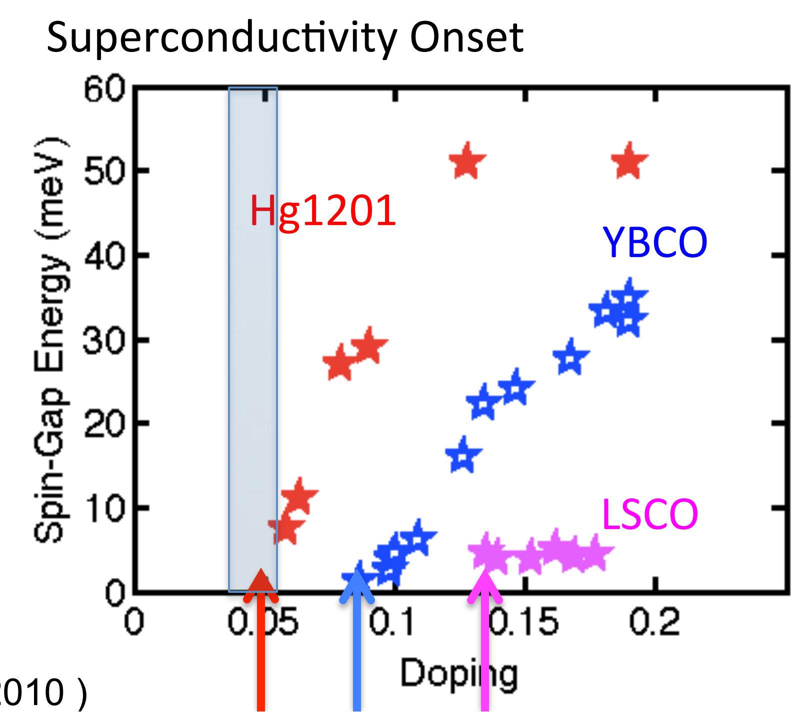
- Magnetic weight decreases with increasing doping

M. K. Chan *et al.* unpublished

What is the magnetic phase diagram?



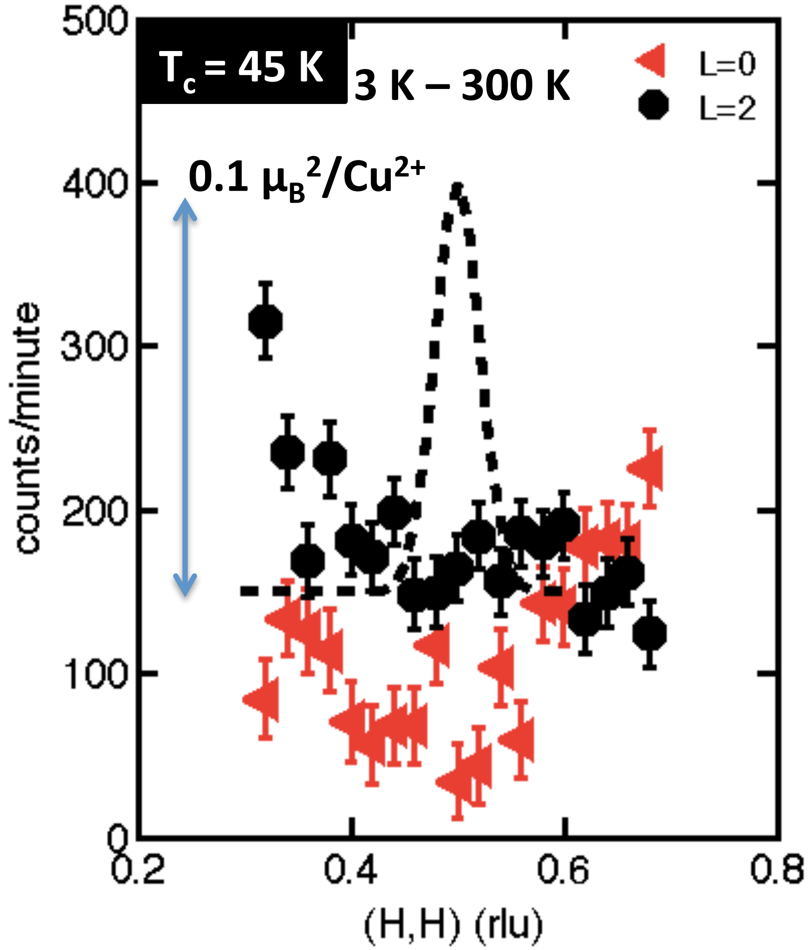




P. Bourges Physica B (1995);
M. Kofu *et al.* PRL (1999); D. Haug *et al.* New Jour. of Phys. (2010)

No static magnetism

PANDA: FRMII



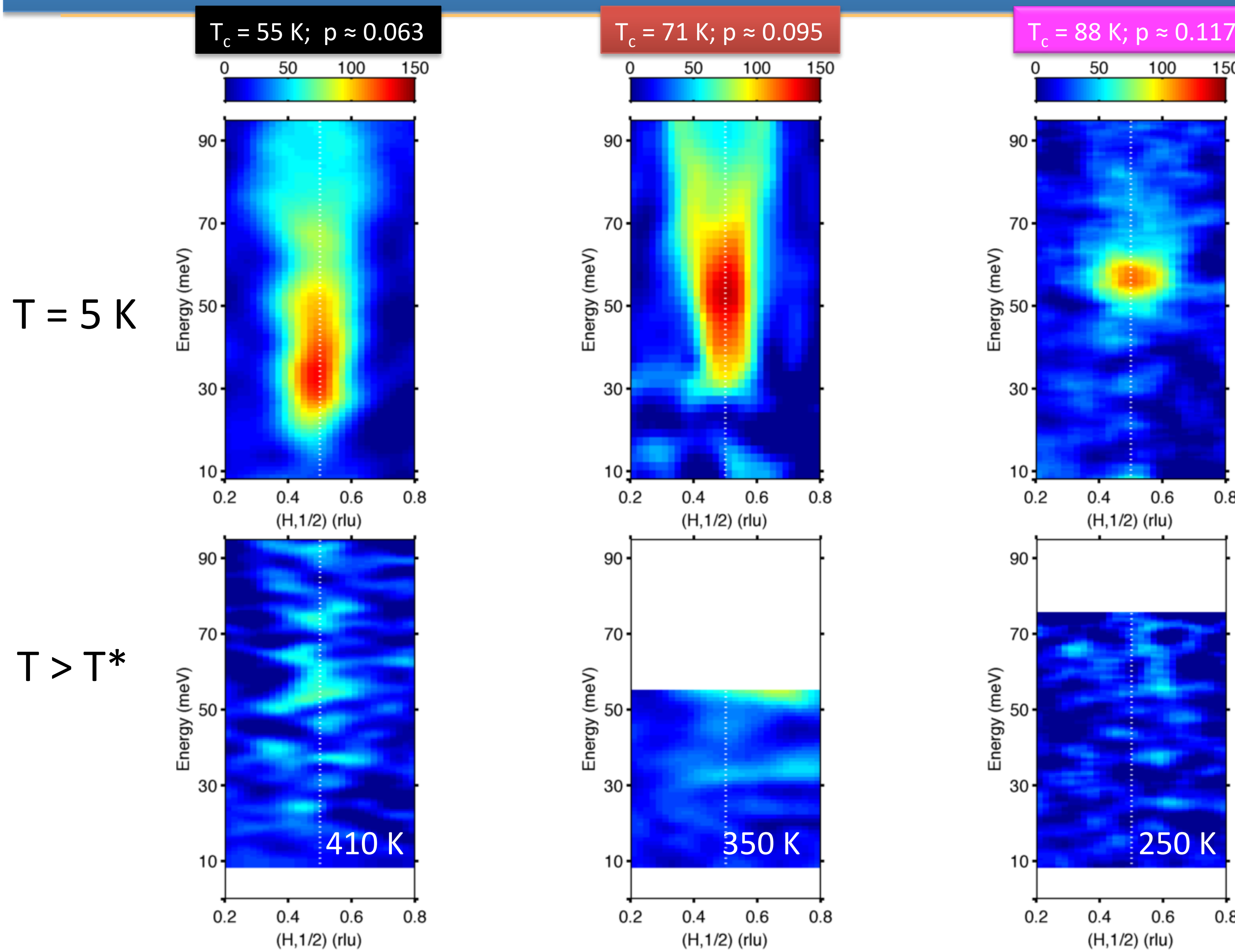
- No commensurate or diagonal elastic response of the same size as in LSCO or YBCO

Neutron: Conclusion 1

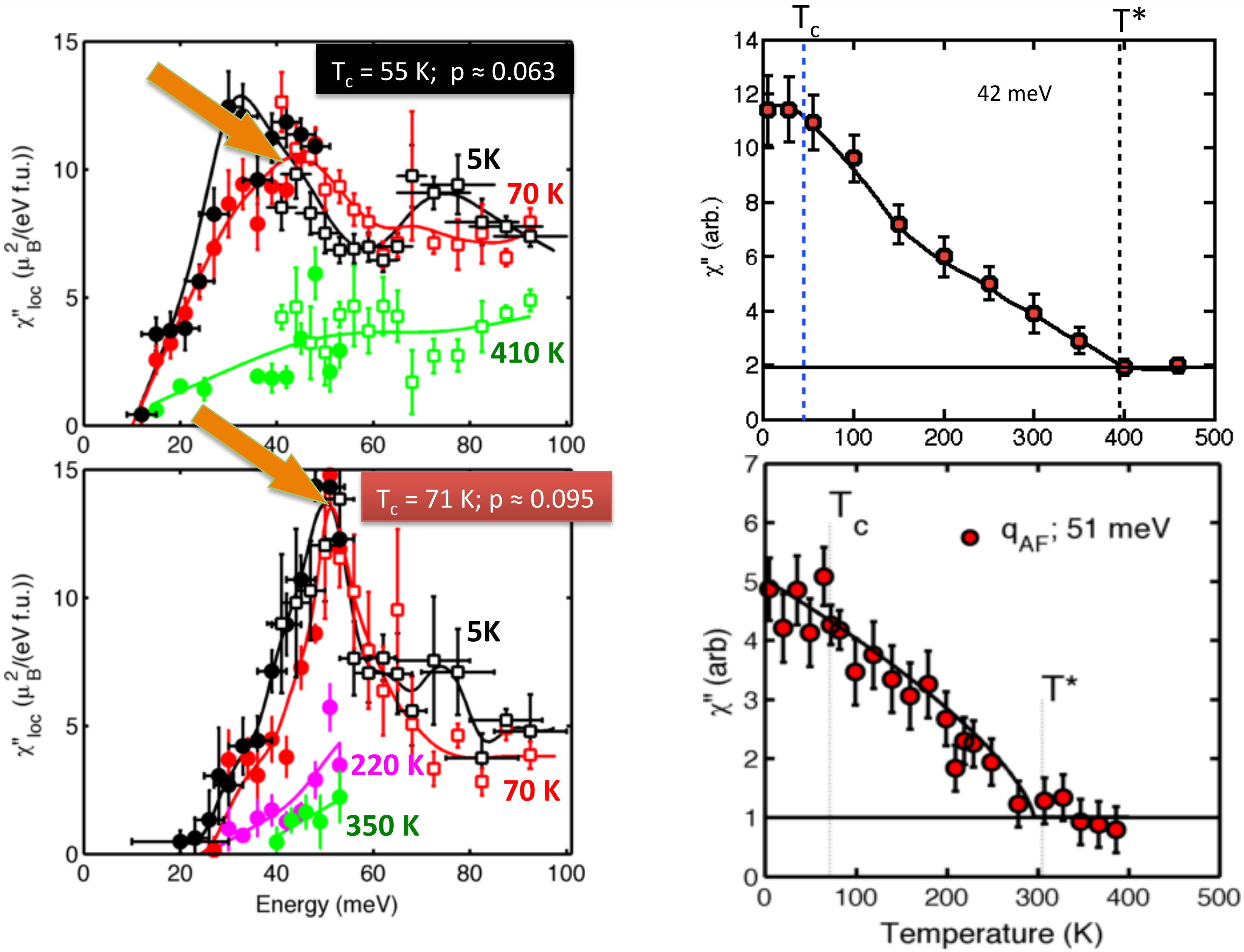
- Low energy commensurate fluctuations: weak or absent stripe correlations

- No static local magnetism in the most underdoped Hg1201 sample studied ($p = 0.058$

Change across T* (pseudogap)



Onset of AF fluctuations



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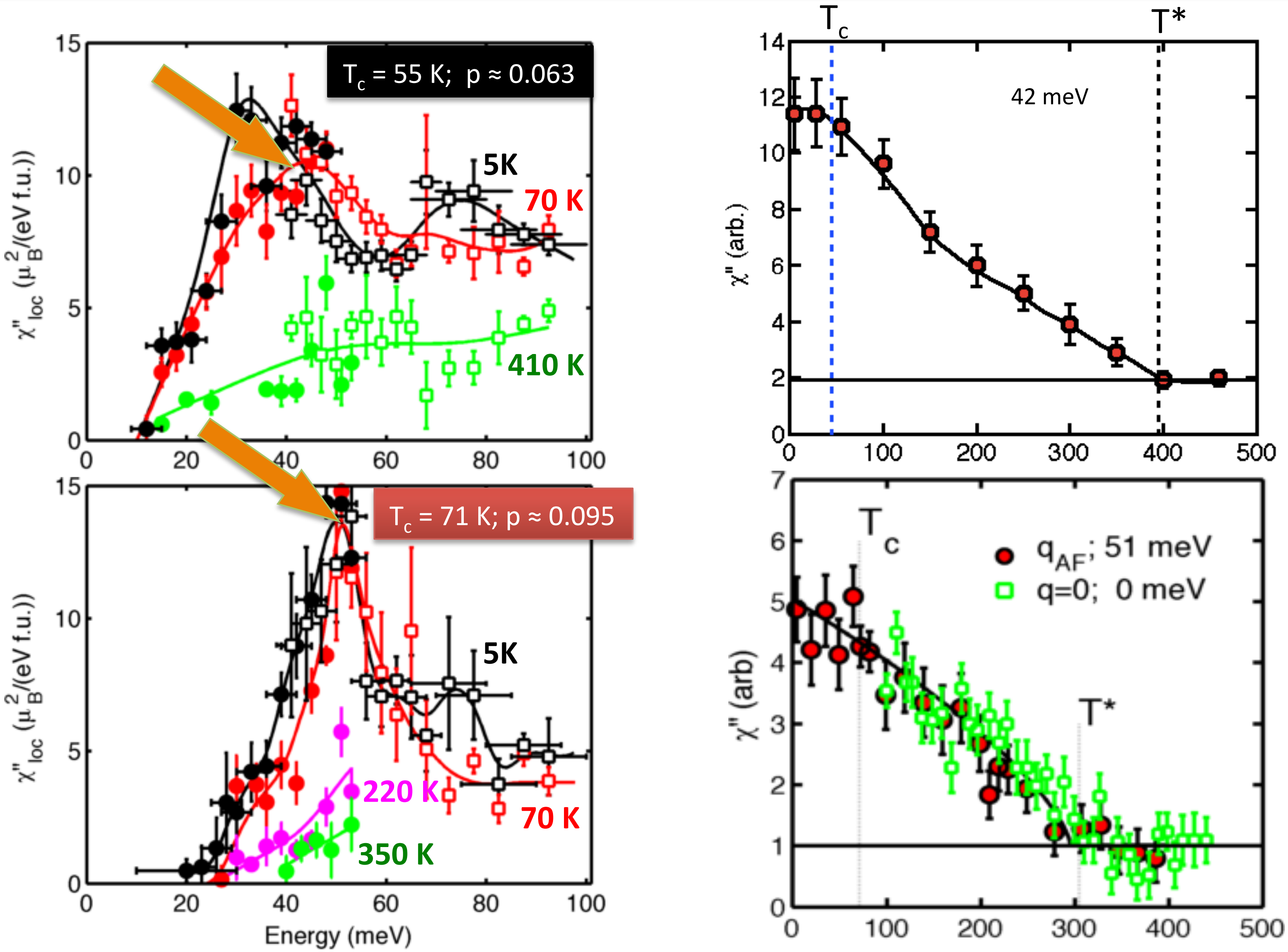


Y. Li. *et al.* PRB (2011)

Neutron: Conclusion 2

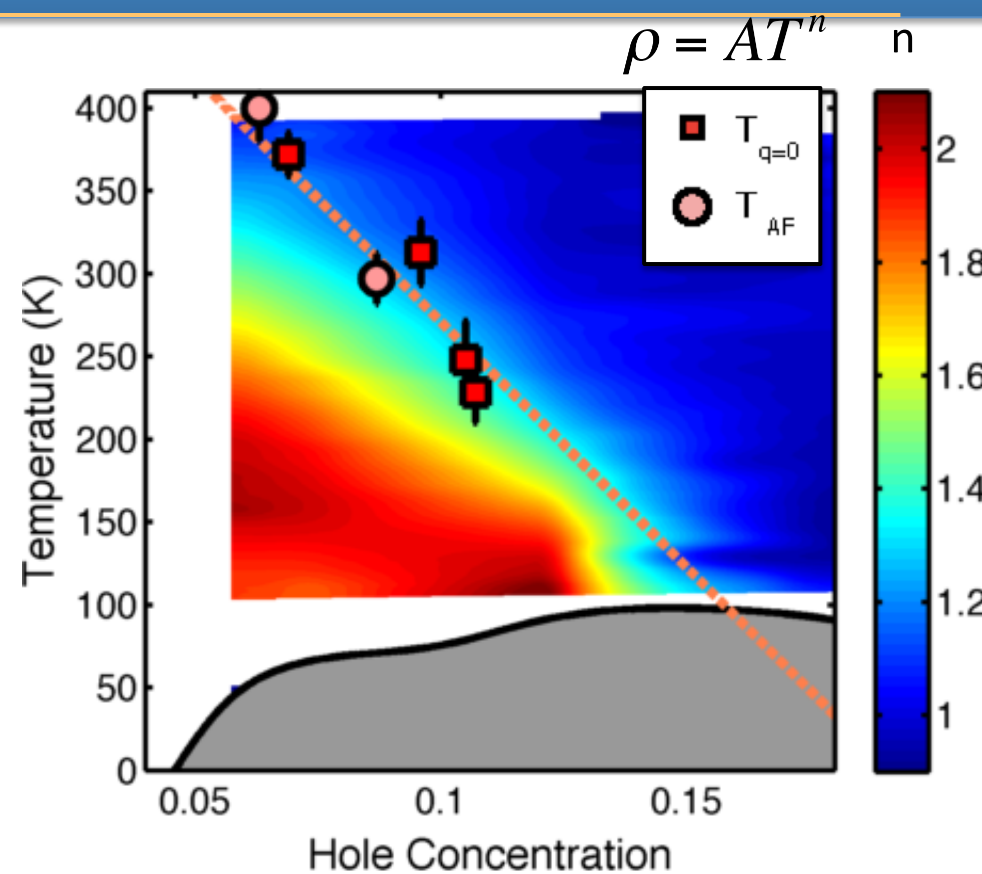
- Low energy commensurate fluctuations: weak or absent stripe correlations
- No static local magnetism in the most underdoped Hg1201 sample studied ($p = 0.058$) : supported by resonance and a spin gap
- Majority of fluctuation weight onsets at the pseudogap temperature T^*

Conclusions

Hg1201: highest Tc, lower disorder, simple tetragonal structure

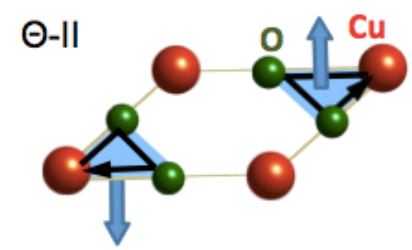
Pseudogap characterized by:

- Fermi-liquid like electrical transport with a largely stable Fermi-surface (w.r.t. temperature)
- Onset of commensurate magnetic fluctuations
- No incommensurate AF ordering

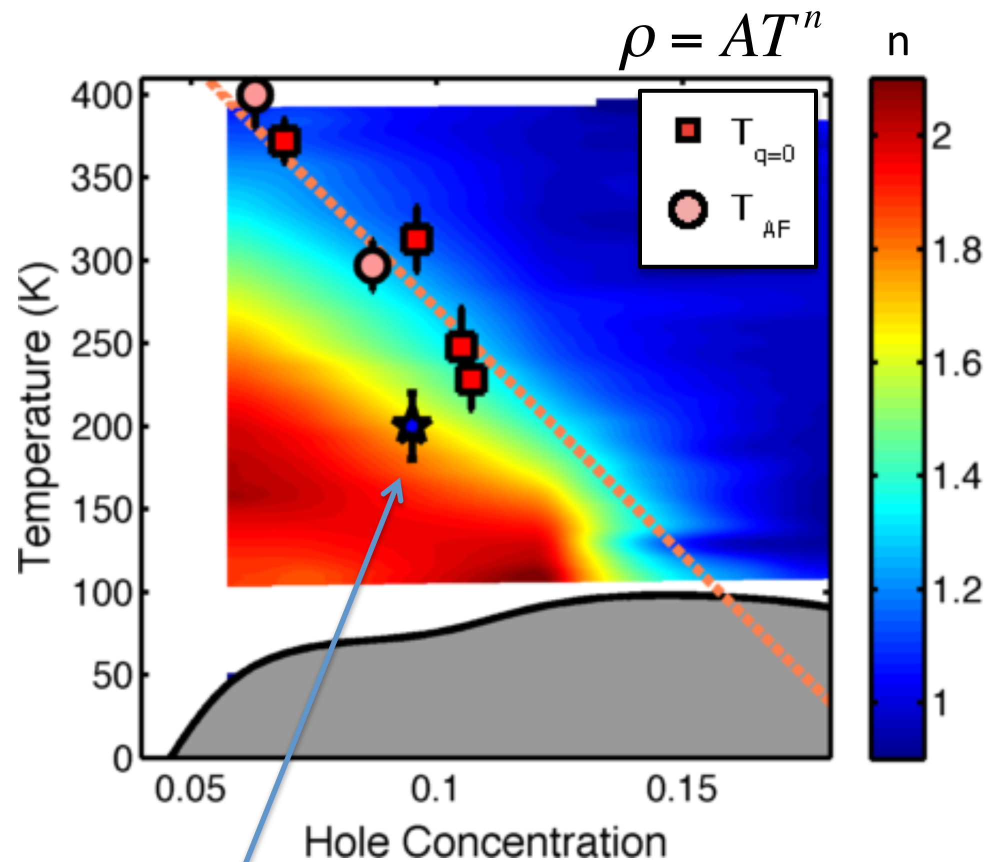


B. Fauqué *et al.* PRL (2006)
Y. Li. *et al.* PRB (2011)
N. Barišić, MKC *et al.* PNAS (2013)

q=0 loop current order



Cuprate phase diagram controlled by AF fluctuations

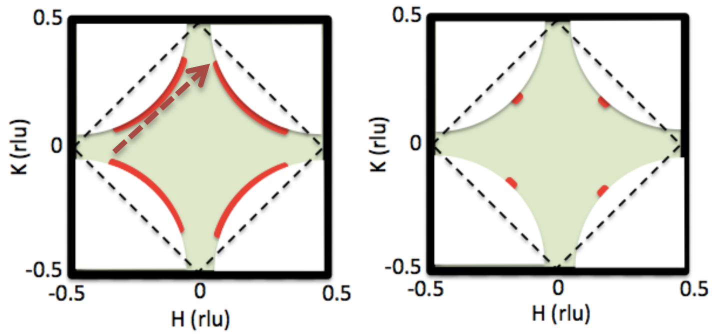


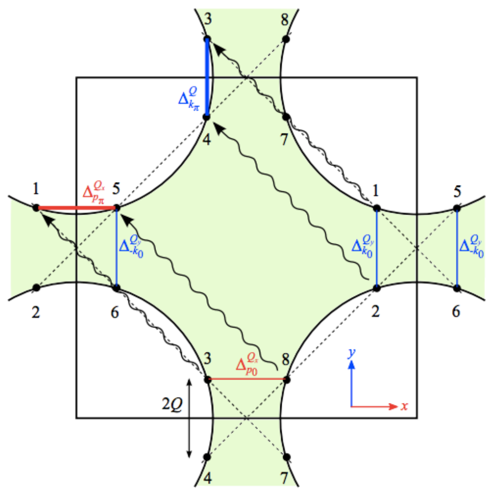
W. Tabis *et al.* arXiv:1404.7658

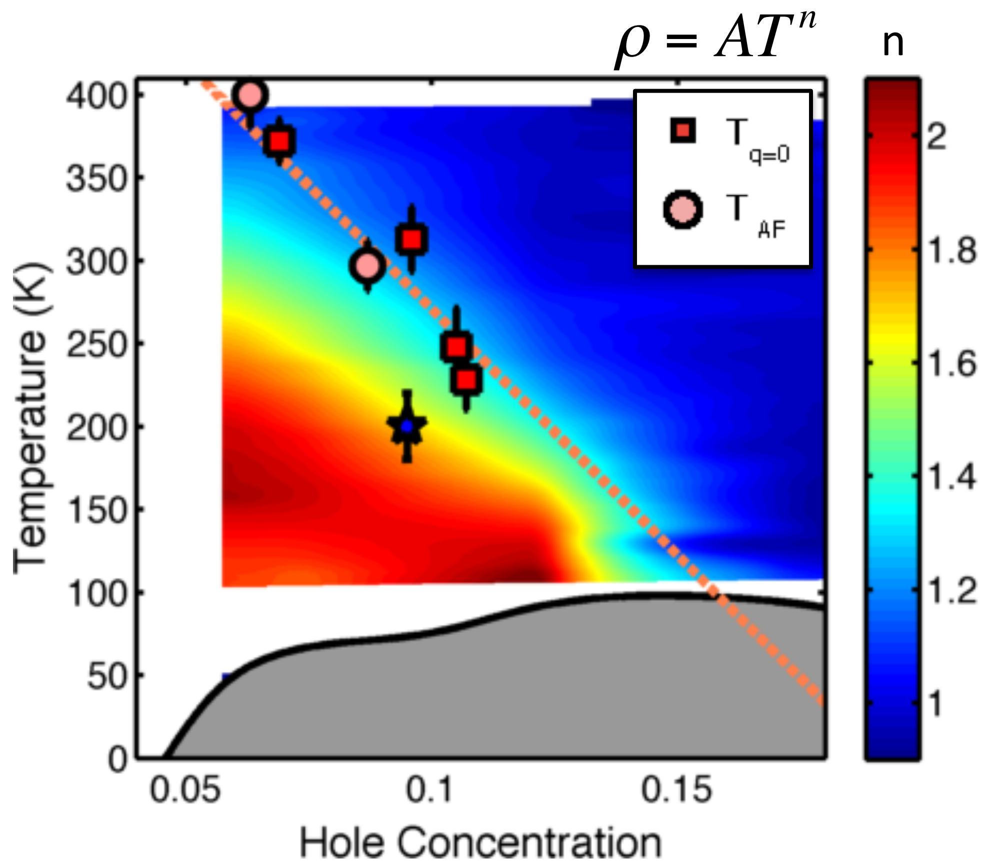
Short-ranged CDW observed in Hg1201

Ghiringhelli *et al.*, Science (2012)
Chang *et al.*, Nature Phys. (2012)

Cuprate phase diagram controlled by AF fluctuations







Y. Wang & A. Chubukov arxiv:1401.0712
M. A. Metlitski & S. Sachdev, PRB (2010).

- Recent and old theoretical proposals based on spin fluctuations
- the hot spots (connected by q_{AF}) near the anti-nodes
- Nodal quasiparticles are Fermi-liquid like